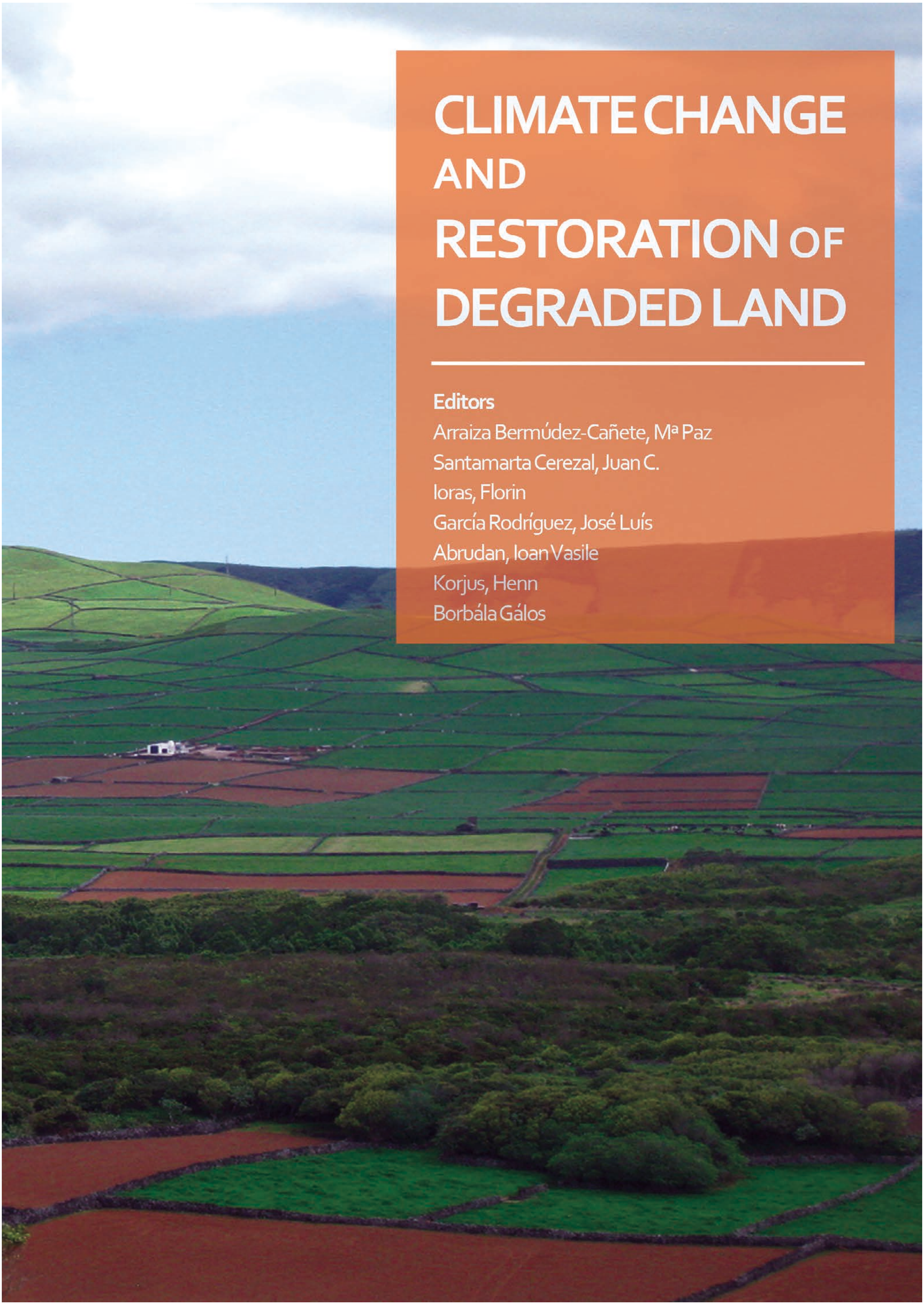

CLIMATE CHANGE AND RESTORATION OF DEGRADED LAND

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Contents

CHAPTER 1
INTRODUCTION TO CLIMATE CHANGE AND LAND DEGRADATION 15

1 Introduction 16

2 Extent and rate of land degradation 17

3 Land degradation – causes 20

4 Climatic consequences of land degradation 21

5 Climatic factors in land degradation 23

5.1 Rainfall

5.2 Floods

5.3 Droughts

5.4 Solar radiation, temperature and evaporation

5.5 Wind

6 Wild fires, land degradation and atmospheric emissions 41

7 Climate change and land degradation 42

7.1 Carbon sequestration to mitigate climate change and combat land degradation

8 Understanding the interactions between climate and land degradation – role of wmo 44

8.1 Advocating for enhanced observing systems at national, regional and international levels

8.2 Promoting effective early warning systems

8.3 Further enhancing climate prediction capability

8.4 Assessing vulnerability and analyzing hazards

8.5 Implementing risk management applications

8.6 Contributing actively to the implementation of the UN system's International Strategy for Disaster Reduction (ISDR)

8.7 Supporting the strengthening of the capabilities of the Parties and regional institutions with drought-related programmes

9 Future perspectives 48

CHAPTER 2.1
REFORESTATION UNDER CLIMATE CHANGE IN TEMPERATE, WATER LIMITED REGIONS: CURRENT VIEWS AND CHALLENGES 55

1 Introduction 56
1.1 Climate, water and forests

2 Effects of forests on hydrological balance in dry regions 58
2.1 China: landcover changes and effects on streamflow
2.2 United States: effects of landcover management
2.3 Hungary: reforestation and its effect on groundwater resources

3 The challenge of changing climate 62
3.1 The climatic transition zone at the forest/grassland edge
3.2 The climatic vulnerability of the forest/grassland transition zone
3.3 Recently observed climatic impacts
3.4 The hidden threat at the xeric limits: increasing drought
3.5 Considerations for forest management

4 Summary and conclusions 67

CHAPTER 2.2
FORESTS IN A CHANGING CLIMATE 71

1 Changes in climate conditions with respect to forest ecology 72
1.1 The threat to xeric limits in SE Europe
1.2 Climatic factors of the xeric distributional limits for beech in SE Europe

2 Growth response to changing climatic conditions 75

3 Response to weather extremes 75
3.1 Health and vitality loss due to climatic extremes: case study of beech in SW Hungary
3.2 Analysis of drought events

4 Projections for the future 79
4.1 Responses validated by field observations

5 Final conclusions 81
5.1 Related websites, projects and videos

CHAPTER 2.3
STRUCTURE AND FUNCTIONING OF FOREST ECOSYSTEMS 85

1 Forest microclimate and microclimate measuring techniques 85
1.1 Introduction
1.2 Syllabus

2 Role of forest cover in the hydrological cycle - case study of measurements and modelling ... 91
2.1 Introduction
2.2 Case study: Comparative Water Balance Study of Forest and Fallow Plots
2.3 Conclusions

3 Carbon cycle: the role of forest vegetation ... 105
3.1 Introduction
3.2 Ecosystem services of forests
3.3 Carbon cycle of forests
3.4 Estimations of the carbon content of forests and forest soil at the xeric limit

4 Biodiversity generation and conservation services - ecosystem, species and genetic diversity ... 117
4.1 Introduction
4.2 Estimation of aridity tolerance from common garden test results
4.3 Discussion

CHAPTER 2.4
CLIMATIC EFFECTS OF LAND COVER CHANGE ... 129

1 Introduction ... 130

2 Literature review ... 131

3 Methods ... 135
3.1 Land Cover Data Arrays
3.2 MM5
3.3 Stratified Sampling

4 Results ... 138

5 Concluding remarks ... 143

6 Related websites, projects and videos ... 144

CHAPTER 2.5
AFFORESTATION AS A TOOL FOR CLIMATE CHANGE MITIGATION ... 147

1 Introduction ... 148
1.1 Regional climate projections for Europe
1.2 Climatic effects of land use and land cover change
1.3 Research foci

2 Methods ... 151
2.1 Experimental setup
2.2 Main steps of the analyses

3 **Results** 154
- 3.1 Climate change signal due to emission change
- 3.2 Climate change signal due to potential afforestation
- 3.3 Climate change signal due to potential afforestation relative to the emission change
- 3.4 Case study for Hungary
- 3.5 Conclusions

4 **Related websites, projects and videos** 158

CHAPTER 3

CLIMATE CHANGE AND WASTE LAND RESTORATION 165

1 **Introduction to climate change and waste land restoration** 165

2 **Waste management and green house gases (ghg)** 166
- 2.1 Background
- 2.2 Sources of GHG
- 2.3 GHG savings
- 2.4 Biogenic carbon

3 **Climate impact of waste** 175
- 3.1 Potential GHG emissions reductions from materials management
- 3.2 Reducing or avoiding GHG emissions through land management practices
- 3.3 Trends in waste generation and management
- 3.4 Climate impact of waste management practices
- 3.5 Waste prevention

4 **Management and minimizing of landfill gas emissions** 201
- 4.1 Closure of landfills
- 4.2 Post-closure maintenance
- 4.3 Minimizing impacts on the atmosphere
- 4.4 Landfill mining

CHAPTER 4

WATER MANAGEMENT AND PLANNING 215

1 **Water planning** 216
- 1.1 Introduction
- 1.2 Water plans
- 1.3 Water plans objetives and strategies
- 1.4 Water budget

1.5 Water planning and climate change
1.6 Water management on islands
1.7 Useful links

2 Water uses **225**

2.1 Introduction
2.2 Water footprint
2.3 Agricultura water uses
2.4 Industrial uses
2.5 Useful links

3 Surface water explotation **229**

3.1 Precipitation
3.2 Reservoir related issues
3.3 Managed aquifer rechargue
3.4 Useful links

4 Water waste, desalination and reuse **234**

4.1 Introduction
4.2 Greywater
4.3 Desalination of water
4.4 Water waste reclamation
4.5 Water waste and climate change
4.6 Useful links

5 Water efficiency and sustainability **240**

5.1 Introduction
5.2 Water efficiency
5.3 Water Sustainability
5.4 Water Efficiency Strategies for Sustainability
5.5 Useful links

6 Water resources and climate change **244**

6.1 Introduction
6.2 Modelling climate change
6.3 Impacts of climate change
6.4 Water quality
6.5 Floods
6.6 Water scarcity and drought

7 European legislation **281**

7.1 Introduction

7.2 European legislation
7.3 Useful links

8 **Miscellaneous Hydrology Studies** 289

CHAPTER 5
EROSION AND HYDROLOGICAL RESTORATION 299

1 **Erosion and Hydrological Restoration** 299
1.1 The origin of the Forest-Hydrologic Restoration Plan (RHF).
1.2 Agro-hydrological Planning.
1.3 RHF Action Planning
1.4 Complementary actions
1.5 Watershed restoration and climate change
1.6 Watershed Management Issues
1.7 Climate Change Science Needs

2 **Design of techniques for water erosion control** 317
2.1 Forest hydrology and watershed management

3 **Adaptation to climate change improving water distribution by land slope techniques** 328

4 **Flood Control in a changing climate** 331
4.1 The European Flood Alert System
4.2 Mortality due to flood events.

CHAPTER 6
FOREST FIRE LAND RESTORATION 345

1 **Postfire Effects on Ecosystems** 345
1.1 Introduction
1.2 Fire Severity
1.3 Fire Regimes
1.4 Fire Effects on Watersheds
1.5 Important Notes

2 **Postfire Assessment Fire Effects Information System** 358
2.1 Introduction
2.2 The Knowledge Base
2.3 Plant Species Information
2.4 Wildlife Species Information
2.5 Plant Community Information

3 **Erosion control. postfire restoration treatments** 372
3.1 Introduction
3.2 Role and Function of Structural Components
3.3 Retaining Structures
3.4 Revetments
3.5 Articulated Block Walls
3.6 Slope Gratings (Three-Dimensional Cellular Grids)
3.7 Postfire Restoration Planning

4 **Study Cases. Postfire Treatments Effectiveness** 388
4.1 Post-Fire Treatment Effectiveness and Treatment Performance
4.2 Hillslope Treatments
4.3 Channel Treatments
4.4 Road Treatments
4.5 Postfire Restoration. A Spanish Case

CHAPTER 7
POLLUTED SOILS RESTORATION.................. 413

1 **Background for effective remediation technologies** 413
1.1 Definition
1.2 Participatory approach in community consultation
1.3 Health risk
1.4 Emissions standards
1.5 Transport and emergency safety assessment
1.6 Impacts of funding

2 **Types of remediation technologies for soils and groundwater** 418
2.1 Thermal desorption
2.2 Excavation or dredging
2.3 Surfactant enhanced aquifer remediation (SEAR)
2.4 Pump and treat
2.5 Solidification and stabilization
2.6 In situ oxidation
2.7 Soil vapor extraction
2.8 Other technologies

3 **Biological degradation** 424

4 **Bioremediation with bacteria, fungus, enzymes** 427
4.1 Basics
4.2 In situ and ex situ bioremediation
4.3 Bioremediation technologies
4.4 Bioremediation monitoring and efficacy testing

5 **Phytoremediation** 447

6 **Metal removal** 451
6.1 Problem
6.2 Sources of contaminants
6.3 Chemical fate and mobility
6.4 Available technologies

CHAPTER 8

COMBATING CLIMATE CHANGE BY RESTORATION OF DEGRADED LAND 483

1 **Restoration of degraded land in the context of climate change: definitions and historical evolution** 483
1.1 Introduction
1.2 Definitions and examples
1.3 Evolution

2 **Carbon fluxes and the restoration of degraded soil** 488
2.1 Introduction
2.2 The terrestrial carbon cycle
2.3 Soil degradation
2.4 Desertification and carbon sequestration

3 **Carbon fluxes and the restoration of degraded agricultural and forest lands** 492
3.1 Restoration of degraded agricultural land
3.2 Restoration of degraded forest land

4 **Mitigating climate change by restoration of degraded lands** 498
4.1 Introduction
4.2 Management Approaches

5 **Adapting restoration of degraded land to climate change** 510

6 **Financial mechanisms to promote restoration of degraded land in the context of climate change** 512
6.1 Introduction
6.2 Financing sources

CHAPTER 9

RESEARCH MATTERS – CLIMATE CHANGE GOVERNANCE 523

1 Scientific basis of climate change 523

1.1 Observations of climate change

1.2 Observed effects of climate change

1.3 Emission scenarios

2 The international response to climate change 531

2.1 Intergovernmental Panel on Climate Change (IPCC)

2.2 United Nations Framework Convention on Climate Change (UNFCCC)

2.3 Kyoto Protocol (KP)

2.4 European Commission – DG Clima

2.5 Combating climate change within and outside the EU

2.6 Adoption of the Kyoto Protocol

2.7 EU and Member States jointly responsible for the quantified emission reduction commitment

2.8 EU monitoring and reporting of greenhouse gas emissions under the UNFCC and the Kyoto Protocol

2.9 European Climate Change Programme

CHAPTER 10

ADVANCED STATISTICS 557

1 Basic Concepts in Statistics 557

1.1 Definition of Statistics

1.2 What is a linear model?

1.3 Definition of a linear model

1.4 Parameter calculus

1.5 Hypothesis test

1.6 Theorem

2 Simple Linear Regression 563

2.1 The Process

2.2 Estimation of the parameters: α_0, α_1, σ^2.

2.3 Simplification tests

2.4 Correlation coefficient

3 Hypothesis tests of the correlation coefficient 571

3.1 Analysis of the residuals

3.2 Independence hypothesis

3.3 Homocedasticity test

4 **Model Evaluation** 577

4.1 Analysis of variance

4.2 Lack of fit test

4.3 Identification of Outliers

4.4 DFFITS

5 **Transformation of a random variable** 586

5.1 Application of the model

Chapter

1

Introduction to Climate Change and Land Degradation

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Chapter 1

Introduction to Climate Change and Land Degradation

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ABSTRACT

The definition of land degradation in the United Nations Convention to Combat Desertification (UNCCD) gives explicit recognition to climatic variations as one of the major factors contributing to land degradation. In order to accurately assess sustainable land management practices, the climate resources and the risk of climate-related or induced natural disasters in a region must be known. Land surface is an important part of the climate system and changes of vegetation type can modify the characteristics of the regional atmospheric circulation and the large-scale external moisture fluxes. Following deforestation, surface evapotranspiration and sensible heat flux are related to the dynamic structure of the low-level atmosphere and these changes could influence the regional, and potentially, global-scale atmospheric circulation. Surface parameters such as soil moisture, forest coverage, transpiration and surface roughness may affect the formation of convective clouds and rainfall through their effect on boundary-layer growth. Land use and land cover changes influence carbon fluxes and GHG emissions which directly alter atmospheric composition and radioactive forcing properties. Land degradation aggravates CO_2-induced climate change through the release of CO_2 from cleared and dead vegetation and through the reduction of the carbon sequestration potential of degraded land.

Climate exerts a strong influence over dry land vegetation type, biomass and diversity. Precipitation and temperature determine the potential distribution of terrestrial vegetation and constitute principal factors in the genesis and evolution of soil. Precipitation also influences vegetation production, which in turn controls the spatial and temporal occurrence of grazing and favours nomadic lifestyle. The generally high temperatures and low precipitation in the dry lands lead to poor organic matter production and rapid oxidation. Low organic matter leads to poor aggregation and low aggregate stability leading to a high potential for wind and water erosion. The severity, frequency, and extent of erosion are likely to be altered by changes in rainfall amount and intensity and changes in wind. Impacts of extreme events such as droughts, sand and dust storms, floods, heat waves, wild fires etc., on land degradation are explained with suitable examples. Current advances in weather and climate science to deal more effectively with the impacts of different climatic parameters on land degradation are explained with suitable examples. Several activities promoted by WMO's programmes around the world help promote a better understanding of the interactions between climate and land degradation through dedicated observations of the climate system; improvements in the application of agro-meteorological methods and the proper assessment and management of water resources; advances in climate science and prediction; and promotion of capacity building in the application of meteorological and hydrological data and information in drought preparedness and management. The definition of land degradation adopted by UNCCD assigns a major importance to climatic factors contributing to land degradation, but there is no concerted effort at the global level to systematically monitor the impacts of different climatic factors on land degradation in different regions and for different classes of land degradation. Hence there is an urgent need to monitor the interactions between climate and land degradation. To better understand these interactions, it is also important to identify the sources and sinks of dryland carbon, aerosols and trace gases in drylands. This can be effectively done through regional climate monitoring networks. Such networks could also help enhance the application of seasonal climate forecasting for more effective dryland management.

1 INTRODUCTION

Desertification is now defined in the United Nations Convention to Combat Desertification (UNCCD) as "land degradation in the arid, semi-arid and dry sub-humid areas resulting from various factors, including climatic variations and human activities" (UNCCD 1999). Furthermore, UNCCD defines land degradation as a "reduction or loss, in arid, semi-arid, and dry subhumid areas, of the biological or economic productivity and complexity of rain-fed cropland, irrigated cropland, or range, pasture, forest, and woodlands resulting from land uses or from a process or combination of processes, including processes arising from human activities and habitation patterns, such as: (i) soil erosion caused by wind and/or water; (ii) deterioration of the physical, chemical, and biological or economic properties of soil; and (iii) long-term loss of natural vegetation."

According to UNCCD, over 250 million people are directly affected by land degradation. In addition, some one billion people in over one hundred countries are at risk. These people include many of the world's poorest, most marginalized, and politically weak citizens.

Land degradation issue for world food security and the quality of the environment assumes a major significance when one considers that only about 11% of the global land surface can be considered as prime or Class I land, and this must feed the 6.3 billion people today and the 8.2 billion expected in the year 2020 (Reich et al. 2001). Hence land degradation will remain high on the international agenda in the 21st century.

Sustainable land management practices are needed to avoid land degradation. Land degradation typically occurs by land management practices or human development that is not sustainable over a period of time. To accurately assess sustainable land management practices, the climate resources and the risk of climate-related or induced natural disasters in a region must be known. Only when climate resources are paired with potential management or development practices can the land degradation potential be assessed and appropriate mitigation technology considered. The use of climate information must be applied in developing sustainable practices as climatic variation is one of the major factors contributing or even a trigger to land degradation and there is a clear need to consider carefully how climate induces and influences land degradation.

2 EXTENT AND RATE OF LAND DEGRADATION

Global assessment of land degradation is not an easy task, and a wide range of methods are used, including expert judgement, remote sensing and modeling. Because of different definitions and terminology, there also exists a large variation in the available statistics on the extent and rate of land degradation. Further, most statistics refer to the risks of degradation or desertification (based on climatic factors and land use) rather than the actual (present) state of the land.

Different processes of land degradation also confound the available statistics on soil and/or land degradation. Principal processes of land degradation (Lal et al. 1989) include erosion by water and wind, chemical degradation (comprising acidification, salinization, fertility depletion, and decrease in cation retention capacity), physical degradation (comprising crusting, compaction, hard-setting etc.) and biological degradation (reduction in total and biomass carbon, and decline in land biodiversity). The latter comprises important concerns related to eutrophication of surface water, contamination of ground water, and emissions of trace gases (CO_2, CH_4, N_2O, NO_x) from terrestrial/aquatic ecosystems to the atmosphere. Soil structure is the important property that affects all degradative processes. Factors that determine the kind of degradative processes include land quality as affected by its intrinsic properties of climate, terrain and landscape position, climax vegetation and biodiversity, especially soil biodiversity.

In an assessment of population levels in the world's dry lands, the Office to Combat Desertification and Drought (UNSO) of the United Nations Development Programme (UNDP) showed that globally 54 million sq. km or 40% of the land area is occupied by dry lands (UNSO 1997). About 29.7% of this area falls in the arid region, 44.3% in the semi-arid region and 26% in the dry sub-humid region. A large majority of the dry lands are in Asia (34.4%) and Africa (24.1%), followed by the Americas (24%), Australia (15%) and Europe (2.5%).

Figure 1 indicates that the areas of the world vulnerable to land degradation cover about 33% of the global land surface. At the global level, it is estimated that the annual income foregone in the areas immediately affected by desertification amounts to approximately US$ 42 billion each year.

The semi-arid to weakly aridic areas of Africa are particularly vulnerable, as they have fragile soils, localized high population densities, and generally a low-input form of agriculture (Lal 1988). About 25% of land in Asian countries is vulnerable.

Long-term food productivity is threatened by soil degradation, which is now severe enough to reduce yields on approximately 16% of the agricultural land, especially cropland in Africa, Central America and pastures in Africa. Sub-Saharan Africa has the highest rate of land degradation. It is estimated that losses in productivity of cropping land in sub-Saharan Africa are in the order of 0.5–1% annually, suggesting productivity loss of at least 20% over the last 40 years (Scherr 1999).

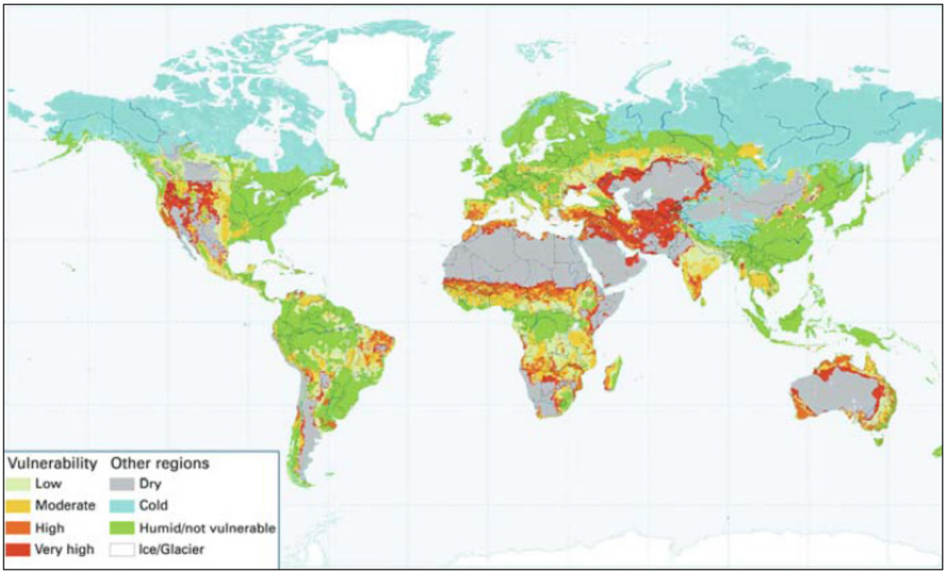

Figure 1. Soil degradation in the world's drylands, 1990s (Source: UNEP)

Africa is particularly threatened because the land degradation processes affect about 46% of Africa (Reich et al. 2001) The significance of this large area becomes evident when one considers that about 43% of the continent is characterized as extreme deserts (the desert margins represent the areas with very high vulnerability.) There is only about 11% of the land mass which is humid and which by definition is excluded from desertification processes. There is about 2.5 million km^2 of land under low risk, 3.6 million km^2 under moderate risk, 4.6 million km^2 under high risk, and 2.9 million km^2 under very high risk. The region that has the highest propensity is located along the desert margins and occupies about 5% of the landmass. It is estimated that about 22 million people (2.9% of total population) live in this area (Reich et al. 2001). The low, moderate and high vulnerability classes occupy 14, 16, and 11% respectively and together impact about 485 million people.

Land degradation is also a serious problem in Australia with over 68% of the land estimated to have been degraded (Table 1).

According to UNCCD, the consequences of land degradation include undermining of food production, famines, increased social costs, decline in the quantity and quality of fresh water supplies, increased poverty and political instability, reduction in land's resilience to natural climate variability and decreased soil productivity.

Table 1. Land degradation on cropland in Australia (Source: Woods, 1983; Mabbutt, 1992)

Type	Area (1.000 km^2)
Total	443
Not degraded	142
Degraded	301
Water erosion	206
Wind erosion	52
Combined water and wind erosion	42
Salinity and water erosion	0.9
Others	0.5

3 LAND DEGRADATION – CAUSES

Land degradation involves two interlocking, complex systems: the natural ecosystem and the human social system (Barrow 1994). Natural forces, through periodic stresses of extreme and persistent climatic events, and human use and abuse of sensitive and vulnerable dry land ecosystems, often act in unison, creating feedback processes, which are not fully understood. Interactions between the two systems determine the success or failure of resource management programs. Causes of land degradation are not only biophysical, but also socioeconomic (e.g. land tenure, marketing, institutional support, income and human health) and political (e.g. incentives, political stability).

High population density is not necessarily related to land degradation. Rather, it is what a population does to the land that determines the extent of degradation. People can be a major asset in reversing a trend towards degradation. Indeed, mitigation of land degradation can only succeed if land users have control and commitment to maintain the quality of the resources. However, they need to be healthy and politically and economically motivated to care for the land, as subsistence agriculture, poverty and illiteracy can be important causes of land and environmental degradation.

There are many, usually confounding, reasons why land users permit their land to degrade. Many of the reasons are related to societal perceptions of land and the values they place on land. The absence of land tenure and the resulting lack of stewardship is a major constraint in some countries to adequate care for the land. Degradation is also a slow imperceptible process and so many people are not aware that their land is degrading.

Loss of vegetation can propagate further land degradation via land surface-atmosphere feedback. This occurs when a decrease in vegetation reduces evaporation and increases the radiation reflected back to the atmosphere (albedo), consequently reducing cloud formation. Large-scale experiments in which numerical models of the general circulation have been run with artificially high albedo over dry lands have suggested that large increases in the albedo of subtropical areas should reduce rainfall.

4 CLIMATIC CONSEQUENCES OF LAND DEGRADATION

Land surface is an important part of the climate system. The interaction between land surface and the atmosphere involves multiple processes and feedbacks, all of which may vary simultaneously. It is frequently stressed (Henderson-Sellers et al. 1993; McGuffie et al. 1995; Sud et al. 1996) that the changes of vegetation type can modify the characteristics of the regional atmospheric circulation and the largescale external moisture fluxes. Changes in surface energy budgets resulting from land surface change can have a profound influence on the earth's climate.

Following deforestation, surface evapotranspiration and sensible heat flux are related to the dynamic structure of the low-level atmosphere. These changes in fluxes within the atmospheric column could influence the regional, and potentially, global-scale atmospheric circulation. For example, changes in forest cover in the Amazon basin affect the flux of moisture to the atmosphere, regional convection, and hence regional rainfall (Lean and Warrilow 1989). More recent work shows that these changes in forest cover have consequences far beyond the Amazon basin (Werth and Avissar 2002).

Fragmentation of landscape can affect convective flow regimes and rainfall patterns locally and globally. El Niño events and land surface change simulations with climate models suggest that in equatorial regions where towering thunderstorms are frequent, disturbing areas hundreds of kilometres on a side may yield global impacts.

Use of a numerical simulation model by Garrett (1982) to study the interactions between convective clouds, the convective boundary layer and a forested surface showed that surface parameters such as soil moisture, forest coverage, and transpiration and surface roughness may affect the formation of convective clouds and rainfall through their effect on boundary-layer growth.

An atmospheric general circulation model with realistic land-surface properties was employed (Dirmeyer and Shukla 1996) to investigate the climatic effect of doubling the extent of earth's deserts and most regions and it showed a notable correlation between decreases in evapotranspiration and resulting precipitation. It was shown that Northern Africa suffers a strong year-round drought while southern Africa has a somewhat weaker year-round drought. Some regions, particularly the Sahel, showed an increase in surface temperature caused by decreased soil moisture and latent-heat flux.

Land use and land cover changes influence carbon fluxes and GHG emissions (Houghton 1995; Braswell et al. 1997) which directly alter atmospheric composition and radiative forcing properties. They also change land-surface characteristics and, indirectly, climatic processes. Observations during the HAPEX-Sahel project suggested that a large-scale transformation of fallow savannah into arable crops like millet, may lead to a decrease in evaporation (Gash et al. 1997). Land use and land cover change is an important factor in determining the vulnerability of ecosystems and landscapes to environmental change.

Since the industrial revolution, global emissions of carbon (C) are estimated at 270±30 gigatons (Gt) due to fossil fuel combustion and 136±5 Gt due to land use change and soil cultivation. Emissions due to land use change include those by deforestation, biomass burning, conversion of natural to agricultural ecosystems, drainage of wetlands and soil cultivation. Depletion of soil organic C (SOC) pool has contributed 78±12 Gt of

C to the atmosphere, of which about one-third is attributed to soil degradation and accelerated erosion and two-thirds to mineralization (Lal 2004).

Land degradation aggravates CO_2-induced climate change through the release of CO_2 from cleared and dead vegetation and through the reduction of the carbon sequestration potential of degraded land.

5 CLIMATIC FACTORS IN LAND DEGRADATION

Climate exerts a strong influence over dry land vegetation type, biomass and diversity (Williams and Balling 1996). Precipitation and temperature determine the potential distribution of terrestrial vegetation and constitute principal factors in the genesis and evolution of soil. Precipitation also influences vegetation production, which in turn controls the spatial and temporal occurrence of grazing and favours nomadic lifestyle. Vegetation cover becomes progressively thinner and less continuous with decreasing annual rainfall. Dry land plants and animals display a variety of physiological, anatomical and behavioural adaptations to moisture and temperature stresses brought about by large diurnal and seasonal variations in temperature, rainfall and soil moisture.

Williams and Balling (1996) provided a nice description of the nature of dryland soils and vegetation and the manner in which climate affects the soils and vegetation. The generally high temperatures and low precipitation in the dry lands lead to poor organic matter production and rapid oxidation. Low organic matter leads to poor aggregation and low aggregate stability leading to a high potential for wind and water erosion. For example, wind and water erosion is extensive in many parts of Africa. Excluding the current deserts, which occupy about 46% of the landmass, about 25% of the land is prone to water erosion and about 22%, to wind erosion.

Structural crusts/seals formed by raindrop impact which could decrease infiltration, increase runoff and generate overland flow and erosion. The severity, frequency, and extent of erosion are likely to be altered by changes in rainfall amount and intensity and changes in wind.

Land management will continue to be the principal determinant of the soil organic matter (SOM) content and susceptibility to erosion during the next few decades, but changes in vegetation cover resulting from short-term changes in weather and near-term changes in climate are likely to affect SOM dynamics and erosion, especially in semi-arid regions.

From the assessment of the land resource stresses and desertification in Africa which was carried out by the Natural Resources Conservation Service of the United States Department of Agriculture (Reich et al. 2001) utilizing information from the soil and climate resources of Africa, it can be concluded (Table 2) that, climatic stresses account for 62.5% of all the stresses on land degradation in Africa. These climatic stresses include high soil temperature, seasonal excess water; short duration low temperatures, seasonal moisture stress and extended moisture stress and affect 18.5 million km^2 of the land in Africa. This study clearly exemplifies the importance of the need to give a more careful consideration of climatic factors in land degradation.

Table 2. Major land resources stresses and land quality assessment of Africa (Source: Reich, P.F., S.T. Numben, R.A. Almaraz, and H. Eswaran. 2001. Land resource stresses and desertification in Africa. In: Eds. Bridges, E.M., I.D. Hannam, F.W.T. Penning de Vries, S.J. Scherr, and S. Sombatpanit. 2001. Response to Land Degradation. Sci. Publishers, Enfield, USA. 101-114)

Land Stresses			Inherent Land Quality		
Stress Class	Kinds of Stress Area	Area (1,000 km2)	Class	Area (1,000 km2)	Area (%)
1	Few constraints	118.1	I	118.1	0.4
2	High shrink/swell	107.6	II		
3	Low organic matter	310.9	II		
4	High soil temperatures	901.0	II	1,319.6	4.5
5	Seasonal excess water	198.9	III		
6	Minor root restrictions	566.5	III		
7	Short duration low temperatures	0.014	III	765.4	2.6
8	Low structural stability	333.7	IV		
9	High anion exchange capacity	43.8	IV		

10	Impeded drainage	520.5	IV	898.0	3.1
11	Seasonal moisture stress	3,814.9	V		
12	High aluminum	1,573.2	V		
13	Calcareous, gypseous	434.2	V		
14	Nutrient leaching	109.9	V	5,932.3	20.2
15	Low nutrient holding capacity	2,141.0	VI		
16	High P, N retention	932.2	VI		
17	Acid sulfate	16.6	VI		
18	Low moisture and nutrient status	0	VI		
19	Low water holding capacity	2,219.5	VI	5,309.3	18.1
20	High organic matter	17.0	VII		
21	Salinity/alkalinity	360.7	VII		
22	Shallow soils	1,016.9	VII	1,394.7	4.8
23	Steep lands	20.3	VIII		
24	Extended low temperatures	0	VIII	20.3	0.1
Land Area		29,309.1			
Water Bodies		216.7			
Total Area		29,525.8			

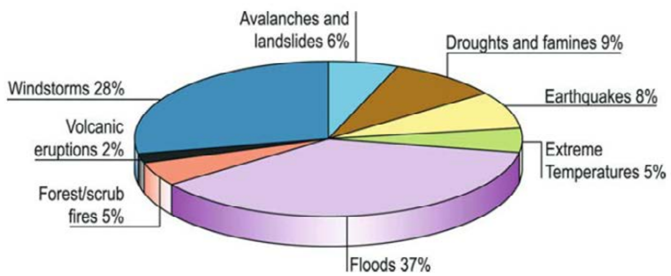

Figure 2. Global distribution of natural disasters (1993-2002)

According to the database of CRED, the Belgium Centre for Research on the Epidemiology of Disasters, weather- climate- and water-related hazards that occurred between 1993-2002, were responsible for 63 per cent of the US$ 654 billion damage caused by all natural disasters. These natural hazards are therefore the most frequent and extensively observed ones (Figure 2) and they all have a major impact on land degradation.

5.1 Rainfall

Rainfall is the most important climatic factor in determining areas at risk of land degradation and potential desertification. Rainfall plays a vital role in the development and distribution of plant life, but the variability and extremes of rainfall can lead to soil erosion and land degradation (Figure 3). If unchecked for a period of time, this land degradation can lead to desertification. The interaction of human activity on the distribution of vegetation though land management practices and seemingly benign rainfall events can make land more vulnerable to degradation. These vulnerabilities become more acute when the prospect of climate change is introduced.

Rainfall and temperature are the prime factors in determining the world's climate and therefore the distribution of vegetation types. There is a strong correlation between rainfall and biomass since water is one of primary inputs to photosynthesis. Climatologists use an "aridity index" (the ratio of annual precipitation to potential evaporation) to help classify desert (arid) or semi-arid areas (UNEP 1992; Williams and Balling 1986; Gringof and Mersha 2006). Drylands exist because the annual water loss (evaporation) exceeds the annual rainfall; therefore these regions have a continual water deficit. Deserts are the ultimate example of a climate where annual evaporation far exceeds the annual rainfall. In cases where the annual water deficits are not so large, some plant life can take hold usually in the form of grasslands or steppes. However, it is these dry lands on the margins of the world's deserts that are most susceptible to desertification, the most extreme example of land degradation. Examples of these regions include the Pampas of South Americas, the Great Russia Steppes, the Great Plains of North America, and the Savannas of Southern Africa and Sahel region of Northern Africa. With normal climatic variability, some years the water deficits can be larger than others but sometimes there can be a several year period of water deficit or long-term drought. During this period, one can see examples of land degradation in the Dust Bowl years of the 1930s in the Great Plains or the nearly two decade long drought in the Sahel in the 1970s and 1980s. It was this period of drought in the Sahel that created the current concern of desertification.

For over a century, soil erosion data has been collected and analyzed from soil scientists, agronomists, geologists, hydrologists, and engineers. From these investigations, scientists have developed a simple soil erosion relationship that incorporates the major soil erosion factors. The Universal Soil Loss Equation (USLE) was developed in the mid-1960s for understanding soil erosion for agricultural applications (Wischmeier and Smith 1978). In the mid-1980's, it was updated and renamed the Revised Universal Soil Loss Equation (RUSLE) to incorporate the large amount of information that had accumulated since the original and to address land use applications besides agriculture such as soil loss from mined lands, constructions sites, and reclaimed lands. The RUSLE is derived from the theory of soil erosion and from more than 10,000 plot-years of data from natural rainfall plots and numerous rainfall simulations.

The RUSLE is defined as:

$$A = R\ K\ L\ S\ C\ P$$

Where A is the soil loss per year (t/ha/year); R represents the rainfall-runoff erosivity factor; K is the soil erodibilty factor; L represents the slope length; S is the slope steepness; C represents the cover management, and P denotes the supporting practices factor (Renard et al. 1997). These factors illustrate the interaction of various climatic, geologic, and human factors and that smart land management practices can minimize soil erosion and hopefully land degradation.

The extremes of either too much or too little rainfall can produce soil erosion that can lead to land degradation. However, soil scientists consider rainfall the most important erosion factor among the many factors that cause soil erosion. Zachar (1982) provides an overview of soil erosion due to rainfall which can erode soil by the force of raindrops, surface and subsurface runoff, and river flooding. The velocity of rain hitting the soil surface produces a large amount of kinetic energy which can dislodge soil particles. Erosion at this micro-scale can also be caused by easily dissoluble soil material made water soluble by weak acids in the rainwater. The breaking apart and splashing of soil particles due to raindrops is only the first stage of the process, being followed by the washing away of soil particles and further erosion caused by flowing water. However, without surface runoff, the amount of soil erosion caused by rainfall is relatively small (Lal 2001).

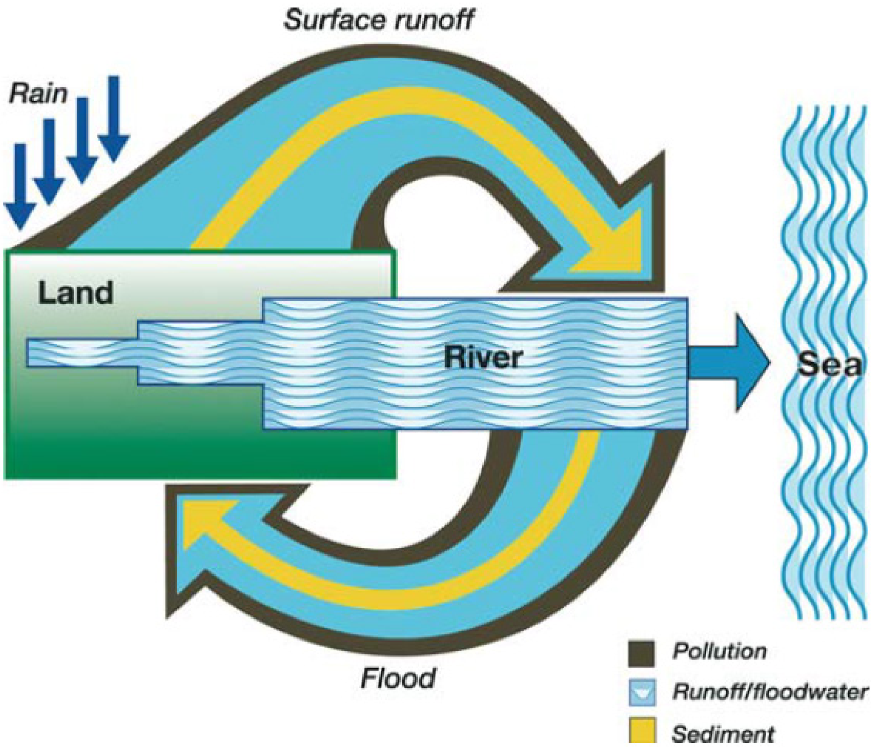

Figure 3. Schematic diagram of rain-fall-induced processes involved in land degradation

Once the soil particles have dislodged they become susceptible to runoff. In general, the higher intensity of the rainfall, the greater is the quantity of soil available in runoff water. In the case of a light rain for a long duration, most of the soil dislodgement takes place in the underwater environment and the soil particles are mostly fine. The greater the intensity of rainfall and subsequent surface runoff, the larger the soil particles that are carried away. A critical factor that determines soil erosion by rainfall is the permeability of the soil, which indirectly influences the total amount of soil loss and the pattern of erosion on slopes. One unfortunate by-product of runoff is the corresponding transport of agricultural chemicals and the leaching of these chemicals into the groundwater.

Rainfall intensity is the most important factor governing soil erosion caused by rain (Zachar 1982). Dry land precipitation is inherently variable in amounts and intensities and so is the subsequent runoff. Surface runoff is often higher in dry lands than in more humid regions due to the tendency of dry land soils to form impermeable crusts under the impact of intense thunderstorms and in the absence of significant plant cover or litter. In these cases, soil transport may be an order of magnitude greater per unit momentum of falling raindrops than when the soil surface is well vegetated. The sparser the plant cover, the more vulnerable the topsoil is to dislodgement and removal by raindrop impact and surface runoff. Also, the timing the rainfall can play crucial role in soil erosion leading to land degradation. An erratic start to the rainy season along with heavy rain will have a greater impact since the seasonal vegetation will not be available to intercept the rainfall or stabilize the soil with its root structure.

An on-going effort of scientists is to try to integrate all these factors into models that can be used to predict soil erosion. The Water Erosion Prediction Project (WEPP) model is a process-based, distributed parameter, continuous simulation, erosion prediction model for use on personal computers and can be applied at the field scale to simulate hillslope erosion or more complex watershed scale erosion (USDA 2006). It mimics the natural processes that are important in soil erosion. It updates the soil and crop conditions every day that affect soil erosion. When rainfall occurs, the plant and soil characteristics are used to determine if surface runoff will occur. The WEPP model includes a number of conceptual components that include: climate and weather (rainfall, temperature, solar radiation, wind, freeze – thaw, snow accumulation and melting), irrigation (stationary sprinkler, furrow), hydrology – (infiltration, depressional storage, runoff), water balance (evapotranspiration, percolation, drainage), soils (types and properties) , crop growth – (cropland, rangeland, forestland), residue management and decomposition, tillage impacts on infiltration and erodibility, erosion – (interrill, rill, channel), deposition (rills, channels, and impoundments), sediment delivery, particle sorting and enrichment.

Of special note is the impact of other forms of precipitation on soil erosion (Zachar 1982). Hail has a severe effect on the soil surface because its kinetic energy is several times that of rain resulting in much more soil surface being destroyed and a greater amount of material being washed away. And if hailstorms are accompanying with heavy rain, as is the case with some thunderstorms, large amounts of soil can be eroded especially on agricultural land before the crops can stabilize the soil surface. Snow thaw erosion occurs when the soil freezes during the cold period and the freezing process dislodges the soil, so that when the spring thaw occurs, fine soil particles are released in the runoff. This kind of erosion can often produce greater erosion losses than by rain. Also, when the soil freezes the infiltration rate is greatly reduced so that when the thaw arrives, relatively intense soil erosion can take place even though the amount of snow thaw is small. In this situation, the erosive processes can be multiplied by a combination of a heavy rain event and sudden influx of warm air. Leeward portions of mountainous areas are susceptible to this since they are typically drier and have less vegetation and are prone to katabatic winds (rapidly descending air from a mountain range warms very quickly).

5.2 Floods

Dryland rivers have extremely variable flows and river discharge and the amount of suspended sediments are highly sensitive to fluctuations in rainfall as well as any changes in the vegetation cover in the basins. The loss of vegetation in the headwaters of dryland rivers can increase sediment load and can lead to dramatic change in the character of the river to a less stable, more seasonal river characterised by a rapidly shifting series of channels. However, rainfall can lead to land degradation in other climates, including sub-humid ones. Excessive rainfall events either produced by thunderstorms, hurricanes and typhoons, or mid-latitude low-pressure systems can produce a large amount of water in a short period of time across local areas. This excess of water overwhelms the local watershed and produces river flooding. Of course, this is a natural phenomenon that has occurred for millions of years and continuously shapes the earth. River flooding occurs in all climates, but it is in dryland areas where the problem is most acute.

Flood forecasting is complex process that must take into account many different factors at the same time, depending on the type and nature of the phenomenon that triggers the flooding. For example, widespread flash floods are often started off by heavy rain falling in one area within a larger area of lighter rain, a confusing situation that makes it difficult to forecast where the worst flood will occur. Forecasting floods caused by the heavy rain or storm surges that can sweep inland as part of a tropical cyclone can also be a complex job, as predictions have to include where they will land, the stage of their evolution and the physical characteristics of the coast.

To make predictions as accurate as possible, National Hydrological Services (NHSs) and National Meteorological Services (NMSs) under the auspices of the WMO undertake flood forecasting based on quantitative precipitation forecasts (QPFs), which have become more accurate in recent years, especially for light and moderate amounts of precipitation, although high amounts and rare events are still difficult to predict. So setting up forecasting systems that integrate predictions for weather with those for water-related events is becoming more of a possibility every day, paving the way for a truly integrated approach.

Forecasting also needs to be a cooperative and multidisciplinary effort. With the many issues and the complexity of factors surrounding floods, flood managers have to join forces with meteorologists, hydrologists, town planners, and civil defense authorities using available integrated models. Determining the socioeconomic impacts of floods will mean taking a close look at construction or other activities in and around river channels. Up-to-date and accurate information is essential, through all the available channels: surface observation, remote sensing and satellite technology as well as computer models.

Flood risk assessment and management have been around for decades but recently there has been a shift to Integrated Flood Management. The defining characteristic of Integrated Flood Management is integration, expressed simultaneously in different forms: an appropriate mix of strategies, points of interventions, types of interventions (i.e. structural or non-structural), short or long-term, and a participatory and transparent approach to decision making – particularly in terms of institutional integration and how decisions are made and implemented within the given institutional structure.

Land use planning and water management have to be combined in one synthesized plan through co-ordination between land management and water management authorities to achieve consistency in planning. The rationale for this integration is that the use of land has impacts upon both water quantity and quality. The three main elements of river basin management – water quantity, water quality, and the processes of erosion and deposition – are inherently linked.

Therefore, an integrated flood management plan should address the following five key elements (APFM 2004):

- Manage the water cycle as a whole;

- Integrate land and water management;
- Adopt a best mix of strategies;
- Ensure a participatory approach;
- Adopt integrated hazard management approaches.

5.3 Droughts

Drought is a natural hazard originating from a deficiency of precipitation that results in a water shortage for some activities or some groups. It is the consequence of a reduction in the amount of precipitation over an extended period of time, usually a season or more in length, often associated with other climatic factors – such as high temperatures, high winds and low relative humidity – that can aggravate the severity of the event. For example, the 2002-03 El Niño related Australian drought (Coughlan et al. 2003), which lasted from March 2002 to January 2003, was arguably one of, if not the, worst short term droughts in Australia's recorded meteorological history (Nicholls 2004). Analysis of rainfall records for this 11-month period showed that 90% of the country received rainfall below that of the long-term median, with 56% of the country receiving rainfall in the lowest 10% (i.e., decile-1) of recorded totals (Australia-wide rainfall records commenced in 1900). During the 2002-03 droughts Australia experienced widespread bushfires, severe dust storms and agricultural impacts that resulted in a drop in Australia's Gross Domestic Product of over 1% (Watkins 2005). The first 5 months of 2005 were exceptionally dry for much of Australia, leading many to label this period a truly exception drought.

Extended droughts in certain arid lands have initiated or exacerbated land degradation. Records show that extensive droughts have afflicted Africa, with serious episodes in 1965–1966, 1972–1974, 1981–1984, 1986–1987, 1991–1992, and 1994–1995. The aggregate impact of drought on the economies of Africa can be large: 8–9 per cent of GDP in Zimbabwe and Zambia in 1992, and 4–6 per cent of GDP in Nigeria and Niger in 1984. In the past 25 years, the Sahel has experienced the most substantial and sustained decline in rainfall recorded anywhere in the world within the period of instrumental measurements. The Sahelian droughts in the early 70s were most unique in their severity and were characterized as "the quintessence of a major environmental emergency" and their long term impacts are now becoming clearer (Figure 4).

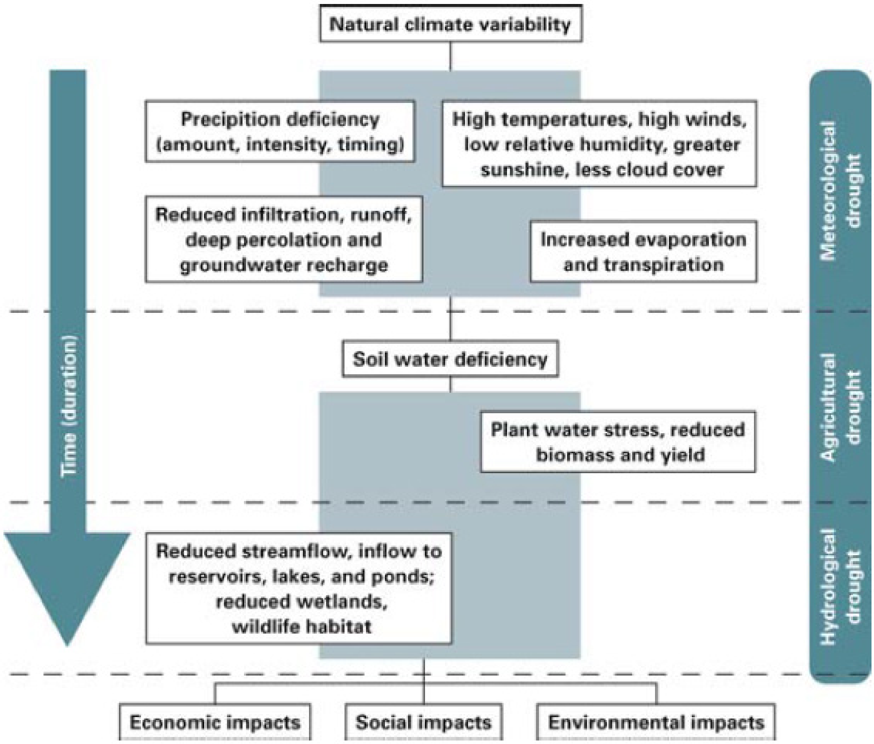

Figure 4. Types and impacts of draught

Sea surface temperature (SST) anomalies, often related to the El Niño Southern Oscillation (ENSO) or North Atlantic Oscillation (NAO), contribute to rainfall variability in the Sahel. Droughts in West Africa correlate with warm SST in the tropical south Atlantic. Examination of the oceanographic and meteorological data from the period 1901-1985 showed that persistent wet and dry periods in the Sahel were related to contrasting patterns of SST anomalies on a near-global scale (Sivakumar 2006). From 1982 to 1990, ENSO-cycle SST anomalies and vegetative production in Africa were found to be correlated. Warmer eastern equatorial Pacific waters during ENSO episodes correlated with rainfall of <1,000 mm yr^{-1} over certain African regions.

A coupled surface-atmosphere model indicates that – whether anthropogenic factors or changes in SST initiated the Sahel drought of 1968-1973 – permanent loss of Sahel savannah vegetation would permit drought conditions to persist. The effect of drought, reducing soil moisture and thus evaporation and cloud cover, and increasing surface albedo as plant cover is destroyed, is generally to increase ground and near-surface air temperatures while reducing the surface radiation balance and exacerbating the deficit in the radiation balance of the local surface-atmosphere system (Williams and Balling 1996). This entails increased atmospheric subsidence and consequently further reduced precipitation.

Early warning systems can reduce impacts by providing timely information about the onset of drought (Wilhite et al. 2000) Conventional surface observation stations within National Meteorological Services are one link in the chain, providing essential benchmark data and time series necessary for improved monitoring of the climate and hydrologic system. Tracking certain indicators such as stream flow or soil moisture can help in formulating drought index values – typically single numbers, far more useful than raw data for decision-making.

Drought plans should contain three basic components: monitoring and early warning, risk assessment, and mitigation and response (Wilhite and Svoboda 2000) . Because of the slow onset characteristics of droughts, monitoring and early warning systems provide the foundation for an effective drought mitigation plan. A plan must rely on accurate and timely assessments to trigger mitigation and emergency response programs.

Various WMO programmes monitor extreme climate events associated with drought, while four monitoring centres – two in Africa, one in China and the Global Information and Early Warning System – provide weather advisories and one and three-month climate summaries. Among other African early warning systems, the Southern Africa Development Community (SADC) monitors the crop and food situation in the region and issues alerts during periods of impending crisis. Such networks can be the backbone of drought contingency planning, coordinated plans for dealing with drought when it comes.

5.4 Solar radiation, temperature and evaporation

The only source of energy for the earth is the sun but our world intercepts only a tiny amount of this energy (less than a tenth of 1 percent) to provide the energy for the various biological (photosynthesis) and geophysical (weather and climate) processes for life depends on. The earth system, based on fundamental rules of physics, must emit the same amount of radiation as it receives. Therefore, the complex transfer of energy to satisfy this requirement is the basis for our weather and climate. Solar radiation is highly correlated with cloudiness, and in most dryland climates there are little or no clouds, the solar radiation can be quite intense. In fact, some of the highest known values of solar radiation can be found in places like the Sahara desert. Solar heating of the land surface is the main contribution to the air temperature.

Along with rainfall, temperature is the main factor determining climate and therefore the distribution of vegetation and soil formation. Soil formation is the product of many factors that include: the parent material (rock), topography, climate, biological activity, and time. Temperature and rainfall cause different patterns of weathering and leaching in soils. Seasonal and daily changes in temperature can affect the soil moisture, biological activity, rates of chemical reactions, and the types of vegetation. Important chemical reactions in the soil include the nitrogen and carbon cycles.

In the tropics, surface soil temperatures can exceed 55°C and this intense heat contributes to the cracking of highly-clay soils that expose not only the soil surface but the soil subsurface to water or wind erosion. Of course, these high temperatures will also increase soil evaporation and further reduce available soil moisture for plant growth.

In temperate dry lands, the freeze-thaw cycle can have a direct effect on the composition of the soil by the movement of rocks and stones from various depths to the surface. In high elevations, the freeze-thaw is one factor degrading rock structures, causing cracks and fissures which could lead to landslides and rock avalanches.

Evaporation is the conversion of water from the liquid or solid state into vapour, and its diffusion into the atmosphere. A vapour pressure gradient between the evaporating surface and the atmosphere and a source of energy are necessary for evaporation. Solar radiation is the dominant source of energy and sets the broad limits of evaporation. Solar radiation values in the tropics are high, modified by the cloud cover, which leads to a high evaporative demand of the atmosphere. In the arid and semi-arid regions, considerable energy may be advected from the surrounding dry areas over irrigated zones. Rosenberg et al. (1983) lists several studies that have demostrated the "oasis effect" which is the transfer of energy across an evaporating surface and can cause large evaporative losses in a short period of time.

Climatic factors induce an evaporative demand of the atmosphere, but the actual evaporation resulting will be influenced by the nature of the evaporating surfaces as well as the availability of water. On a degraded land, the land surface itself influences the evaporative demand by the albedo and surface roughness, the latter affecting turbulence. In the arid and semi-arid regions, the high evaporation which greatly exceeds precipitation leads to accumulation of salts on soil surface. Soils with natric horizon are easily dispersed and the low moisture levels lead to limited biological activity.

5.5 Wind

The dry lands of the world are affected by moderate to severe land degradation from wind erosion and there is evidence that the frequency of sand storms/dust storms in increasing. It has been estimated that in the arid and semi-arid zones of the world, 24% of the cultivated land and 41% of the pasture land are affected by moderate to severe land degradation from wind erosion (Rozanov 1990).

The world-wide total annual production of dust by deflation of soils and sediments was estimated to be 61 to 366 million tonnes (Middleton 1986). Losses of desert soil due to wind erosion are globally significant. The upper limit for global estimates of the long-range transport of desert dust is approximately 1 x 1016 g year $^{-1}$.

For Africa, it is estimated that more than 100 million tonnes of dust per annum is blown westward over the Atlantic. The amount of dust arising from the Sahel zone has been reported to be around or above 270 million tons per year which corresponds to a loss of 30 mm per m2 per year or a layer of 20 mm over the entire area (Stahr et al. 1996).

Every year desert encroachment caused by wind erosion buries 210,000 hectares of productive land in China (PRC 1994). It was shown that the annual changes of the frequency of strong and extremely strong sandstorms in China are as follows: 5 times in the 1950s, 8 times in the 1960s, 13 times in the 1970s, 14 times in the 1980s, and 20 times in the 1990s (Ci 1998).

Sand and dust storms are hazardous weather and cause major agricultural and environmental problems in many parts of the world. There is a high on-site as well as off-site cost due to the sand and dust storms. They can move forward like an overwhelming tide and strong winds take along drifting sands to bury farmlands, blow out top soil, denude steppe, hurt animals, attack human settlements, reduce the temperature, fill up irrigation canals and road ditches with sediments, cover the railroads and roads, cause household dust damages, affect the quality of water in rivers and streams, affect air quality, pollute the atmosphere and destroy mining and communication facilities. They accelerate the process of land degradation and cause serious environment pollution and huge destruction to ecology and living environment (Wang Shigong et al. 2001). Atmospheric loading of dust caused by wind erosion also affects human health and environmental air quality.

Wind erosion-induced damage includes direct damage to crops through the loss of plant tissue and reduced photosynthetic activity as a result of sandblasting, burial of seedlings under sand deposits, and loss of topsoil (Fryrear 1971; Amburst 1984; Fryrear 1990). The last process is particularly worrying since it potentially affects the soil resource base and hence crop productivity on a long-term basis, by removing the layer of soil that is inherently rich in nutrients and organic matter. Wind erosion on light sandy soils can provoke severe land degradation and sand deposits on young seedlings can affect crop establishment.

Calculations based on visibility and wind speed records for 100 km wide dust plumes, centered on eight climate stations around South Australia, indicated that dust transport mass was as high as 10 million tonnes (Butler et al. 1994). Thus dust entrainment during dust events leads to long-term soil degradation, which is essentially irreversible. The cost to productivity is difficult to measure but is likely to be quite substantial.

5.5.1 Causes of wind erosion

The occurrence of wind erosion at any place is a function of weather events interacting with soil and land management through its effects on soil structure, tilth and vegetation cover. In regions where long dry periods associated with strong seasonal winds occur regularly, the vegetative cover of the land does not sufficiently protect the soil, and the soil surface is disturbed due to inappropriate management practices, wind erosion usually is a serious problem.

At the southern fringe of the Sahara Desert, a special dry and hot wind, locally termed Harmattan, occurs. These NE or E winds normally occur in the winter season under a high atmospheric pressure system. When the wind force of Harmattan is beyond the threshold value, sand particles and dust particles will be blown away from the land surface and transported for several hundred kilometres to the Atlantic Ocean.

In the Northwest region of India, the convection sand-dust storm that occurs in the season preceding the monsoon is named Andhi (Joseph et al. 1980). It is called Haboob in Africa and Arabic countries. It is titled "phantom" or "devil" in some regions.

In general, two indicators, wind velocity and visibility, are adopted to classify the grade of intensity of sand-dust storms. For instance, the sand-dust storms occurring in the Northwest part of India are classified into three grades. The feeble sand-dust storm develops when wind velocity is at force 6 (Beaufort) degree and visibility varies between 500-1,000 m. The secondary strong sand-dust storm will occur when wind velocity is at force 8 and visibility varies 200-500 m. Strong sanddust storms will take place when wind velocity is at force 9 and visibility is <200 metres.

In China, a sand-dust storm is defined similarly to the above. The only difference is that the category of strong sand-dust storms is defined again into two grades, namely strong sand-dust storms and serious-strong sand-dust storms. When wind velocity is 50 metres per second (m/s) and visibility is <200 metres, the sandstorm is called a strong sand-dust storm. When wind velocity is 25 m/s and visibility is 0-50 metres, the sandstorm is termed a serious sand-dust storm (some regions name it Black windstorm or Black Devil) (Xu Guochang et al. 1979).

Four definitions of the dust phenomena are the same as used by the Australian Bureau of Meteorology, which conforms to the worldwide standards of the World Meteorological Organization (WMO). SYNOP present weather [WW] codes are included:

1. Dust storms (SYNOP WW code: 09) are the result of turbulent winds raising large quantities of dust into the air and reducing visibility to less than 1,000 m.

2. Blowing dust (SYNOP WW code: 07) is raised by winds to moderate heights above the ground reducing visibility at eye level (1.8 m), but not to less than 1,000 m.

3. Dust haze (SYNOP WW code: 06) is produced by dust particles in suspended transport which have been raised from the ground by a dust storm prior to the time of observation.

4. Dust swirls (or dust devils) (SYNOP WW code: 08) are whirling columns of dust moving with the wind and usually less than 30 m high (but may extend to 300 m or more). They usually dissipate after travelling a short distance.

Wind erosivity is the main factor controlling the broad pattern of wind erosion. It has been defined as "that property of the wind which determines its ability to entrain and move bare, dry soil in fine tilth" (Painter 1978). It can be estimated from daily or hourly records of wind speed above a threshold related to the lowest speed at which soil particles are entrained (Skidmore and Woodruff 1968). Chepil and Woodruff (1963) developed an index of wind erosion capacity (C) defined as:

$$C = \frac{V^3}{2.9(P - E_2)}$$

where V = wind speed at standard observing levels (~ 10 m), m s-1; P = precipitation (mm); and Ep is potential evapotranspiration (mm). Table 3 gives a classification of the wind erosion capacity as per the different values of the index of wind erosion capacity.

Table 3. Wind erosion capacity

Index value	Wind erosion capacity
0-20	Insignificant or zero
20-50	Moderate
50-150	High
>150	Very high

When soil movement is sustained, the quantity of soil that can be transported by the wind varies as the cube of the velocity. Models demonstrate that wind erosion increases sharply above a threshold wind speed. In the U.S. corn belt, a 20% increase in mean wind speed greatly increases the frequency with which the threshold is exceeded and thus the frequency of erosion events.

There have been several efforts to integrate all these wind erosion factors into a computer model. One such effort is the Wind Erosion Prediction System (WEPS) which is a process-based, daily time-step model that predicts soil erosion by simulation of the fundamental processes controlling wind erosion (Wagner 1996). The WEPS model is able to calculate soil movement, estimate plant damage, and predict PM-10 emissions when wind speeds exceed the erosion threshold. It also provides users with spatial information regarding soil flux, deposition, and loss from specific regions of a field over time. The structure of WEPS is modular and consists of seven submodels and four databases. Most of the WEPS submodels use daily weather as the natural driving force for the physical processes that change field conditions. The other submodels focus on hydrology including the changes in temperature and water status of the soil; soil properties; growth of crop plants; crop plant decomposition; typical management practices such as tillage, planting, harvesting, and irrigation; finally the power of the wind on a subhourly basis.

5.5.2 Climatic implications of dust storms

The very fine fraction of soil-derived dust has significant forcing effects on the radiative budget. Dust particles are thought to exert a radiative influence on climate directly through reflection and absorption of solar radiation and indirectly through modifying the optical properties and longevity of clouds. Depending on their properties and in what part of the atmosphere they are found, dust particles can reflect sunlight back into space and cause cooling in two ways. Directly, they reflect sunlight back into space, thus reducing the amount of energy reaching the surface. Indirectly, they act as condensation nuclei, resulting in cloud formation (Pease et al. 1998). Clouds act as an "atmospheric blanket," trapping long wave radiation within the atmosphere that is emitted from the earth. Thus, dust storms have local, national and international implications concerning global warming. Climatic changes in turn can modify the location and strength of dust sources.

6 WILD FIRES, LAND DEGRADATION AND ATMOSPHERIC EMISSIONS

Uncontrolled wildfires occur in all vegetation zones of the world. It is estimated that fires annually affect 1015 million hectares (m ha) of boreal and temperate forest and other lands, 2040 m ha of tropical rain forests due to forest conversion activities and escaped agricultural fires, and up to 500 m ha of tropical and subtropical savannas, woodlands, and open forests. The extent of the soil organic carbon pool doubles that present in the atmosphere and is about two to three times greater than that accumulated in living organisms in all Earth's terrestrial ecosystems. In such a scenario, one of the several ecological and environmental impacts of fires is that they are a significant source of greenhouse gases responsible for global warming.

Globally, biomass burning, which includes wild fires, is estimated to produce 40 percent of the carbon dioxide, 32 percent of the carbon monoxide, 20 percent of the particulates, and 50 percent of the highly carcinogenic poly-aromatic hydrocarbons produced by all sources (Levine 1990). Current approaches for estimating global emissions are limited by accurate information on area burned and fuel available for burning.

Emissions from fires are considerable and contribute significantly to gross global emissions of trace gases and particulates from all sources to atmosphere. Natural emissions are responsible for a major portion of the compounds, including non-methane volatile organic compounds (NMVOC), carbon monoxide (CO) and nitric oxide (NO), which determine tropospheric oxidant concentrations. The total NMVOC flux is estimated to be about 84×1012 g of carbon (Tg C) which is comprised primarily of isoprene (35%), 19 other terpenoid compounds (25%) and 17 non-terpenoid compounds (40%).

The influence of fire on soil characteristics (soil-water content, soil compaction, soil temperature, infiltration ability, soil properties especially organic matter, pH, exchangeable Ca, Mg, K, Na and extractable P) of a semi-arid southern African rangeland was quantified over two growing seasons (2000/01–2001/02) following an accidental fire (Snyman 2003). The decrease in basal cover due to fire (head fires) exposed the soil more to the natural elements and therefore to higher soil temperatures and soil compaction in turn leading to lower soil-water content and a decline in soil infiltrability.

7 CLIMATE CHANGE AND LAND DEGRADATION

Human activities – primarily burning of fossil fuels and changes in land cover – are modifying the concentration of atmospheric constituents or properties of the Earth's surface that absorb or scatter radiant energy. In particular, increases in the concentrations of greenhouse gases (GHGs) and aerosols are strongly implicated as contributors to climatic changes observed during the 20th century and are expected to contribute to further changes in climate in the 21st century and beyond. These changes in atmospheric composition are likely to alter temperatures, precipitation patterns, sea level, extreme events, and other aspects of climate on which the natural environment and human systems depend.

According to IPCC (2003), established by WMO and UNEP, ecosystems are subject to many pressures (e.g., land-use change, resource demands, population changes); their extent and pattern of distribution is changing, and landscapes are becoming more fragmented. Climate change constitutes an additional pressure that could change or endanger ecosystems and the many goods and services they provide. Soil properties and processes – including organic matter decomposition, leaching, and soil water regimes – will be influenced by temperature increase. Soil erosion and degradation are likely to aggravate the detrimental effects of a rise in air temperature on crop yields. Climate change may increase erosion in some regions, through heavy rainfall and through increased wind speed.

CO_2-induced climate change and land degradation remain inextricably linked because of feedbacks between land degradation and precipitation. Climate change might exacerbate land degradation through alteration of spatial and temporal patterns in temperature, rainfall, solar radiation, and winds. Several climate models suggest that future global warming may reduce soil moisture over large areas of semiarid grassland in North America and Asia (Manabe and Wetherald 1986). This climate change is likely to exacerbate the degradation of semiarid lands that will be caused by rapidly expanding human populations during the next decade. Emmanuel (1987) predicted that there will be a 17% increase in the world area of desert land due to the climate change expected with a doubling of atmospheric CO_2 content.

Water resources are inextricably linked with climate, so the prospect of global climate change has serious implications for water resources and regional development (Riebsame et al. 1995). Climate change – especially changes in climate variability through droughts and flooding – will make addressing these problems more complex.

The greatest impact will continue to be felt by the poor, who have the most limited access to water resources. The impact of changes in precipitation and enhanced evaporation could have profound effects in some lakes and reservoirs. Studies show that, in the paleoclimate of Africa and in the present climate, lakes and reservoirs respond to climate variability via pronounced changes in storage, leading to complete drying up in many cases. Furthermore, these studies also show that under the present climate regime several large lakes and wetlands show a delicate balance between inflow and outflow, such that evaporative increases of 40%, for example, could result in much reduced outflow.

The frequency of episodic transport by wind and water from arid lands is also likely to increase in response to anticipated changes in global climate (Manabe and Wetherald 1986). Lower soil moisture and sparser vegetative cover would leave soil more susceptible to wind erosion. Reduction of organic matter inputs and increased oxidation of SOM could reduce the long-term water-retention capacity of soil, exacerbating desertification. Moreover, increased wind erosion increases wind-blown mineral dust, which may increase absorption of radiation in the atmosphere (Nicholson and Kim 1997).

7.1 Carbon sequestration to mitigate climate change and combat land degradation

The soil organic carbon (SOC) pool to 1-m depth ranges from 30 tons ha^{-1} in the arid climates to 800 tons ha^{-1} in organic soils in cold regions (Lal 2007). Conversion of natural to agricultural ecosystems causes depletion of SOC pool by as much as 60% in soils of temperate regions and 75% or more in the cultivated soils of the tropics. The depletion is exacerbated when the output of carbon (C) exceeds the input and when soil degradation is severe.

Carbon sequestration implies transferring atmospheric CO_2 into long-lived pools and storing it securely so it is not immediately reemitted. Thus, soil C sequestration means increasing SOC and soil inorganic carbon stocks through judicious land use and recommended management practices. Some of these practices include mulch farming, conservation tillage, agroforestry and diverse cropping systems, cover crops and integrated nutrient management, including the use of manure, compost, biosolids, improved grazing, and forest management.

The potential carbon sink capacity of managed ecosystems approximately equals the cumulative historic C loss estimated at 55 to 78 gigatons (Gt). Offsetting fossilfuel emissions by achievable SOC potential provides multiple biophysical and societal benefits. An increase of 1 ton of soil carbon of degraded cropland soils may increase crop yield by 20 to 40 kg ha^{-1} for wheat, 10 to 20 kg ha^{-1} for maize, and 0.5 to 1 kg ha^{-1} for cowpeas and could enhance world food security (Lal 2007).

8 UNDERSTANDING THE INTERACTIONS BETWEEN CLIMATE AND LAND DEGRADATION – ROLE OF WMO

WMO is the United Nations specialized agency responsible for meteorology and operational hydrology. WMO provides support to the National Meteorological and Hydrological Services (NMHSs) of its 188 Member States and Territories in their respective missions of observing and understanding weather and climate and providing meteorological and related services in support of national needs. These needs especially relate to protection of life and property, safeguarding the environment and contributing to sustainable development.

The scientific programmes of WMO have been vital in expanding knowledge of the climate system. The systematic observations carried out using standardized methods have provided worldwide data for analysis, research and modelling of the atmosphere and its changing patterns of weather systems. WMO coordinates a global network for the acquisition and exchange of observational data under the Global Observing System of its World Weather Watch Programme. The system comprises some 10 000 stations on land, 1 000 upper-air stations, 7 000 ships, some 3 000 aircraft providing over 150 000 observations daily and a constellation of 16 meteorological, environmental, operational and research satellites. WMO also coordinates a network of three World Meteorological Centres, 35 Regional Specialized Meteorological Centres and 187 National Meteorological Centres. Specialized programmes of observations, including those for chemical constituents of the atmosphere and characteristics of the oceans and their circulations, have led to a better understanding of interactions between the domains of the climate system (the atmosphere, the oceans, the land surface and the cryosphere) and of climate variability and change.

Specifically, WMO contributes to understanding the interactions between climate and land degradation through dedicated observations of the climate system; improvements in the application of agrometeorological methods and the proper assessment and management of water resources; advances in climate science and prediction; and promotion of capacity building in the application of meteorological and hydrological data and information in drought preparedness and management. In this context, WMO will continue to address the issue of land degradation through its Agricultural Meteorology Programme, Hydrology and Water Resources Programme, and other scientific and technical programmes by:

8.1 Advocating for enhanced observing systems at national, regional and international levels

WMO is committed to work with the Parties to the UNCCD to improve the observing systems for weather, climate and water resources in order to meet the needs of the Convention, and to assist developing countries to strengthen their participation in the collection and use of these observations to meet their commitments to the Convention. In this regard, it is quite relevant to examine the Decisions of the Conference of Parties of the United Nations Framework Convention on Climate Change (UNFCCC) which address the issue of climate observing systems, and the regional workshop programme that has been developed and is being implemented in different parts of the world by the Global Climate Observing System (GCOS) Secretariat co-sponsored by WMO.

8.2 Promoting effective early warning systems

Early warning systems serve as an essential and important alert mechanism for combating land degradation. As meteorological and hydrological hazards are linked with climate variability, regular assessments and authoritative statements on the interpretation and applicability of observational data are needed for the study of climate variability and the implementation of a climate alert system to allow NMHSs to make early warnings on pending significant climate anomalies. Warnings of climate-related disasters are becoming feasible from weeks to seasons in advance. WMO's World Climate Programme will continue to issue routine statements on the state of El Niño or La Niña, which, through the NMHSs, can alert Governments to ensure preparedness against the impacts of El Niño-related anomalies, which can trigger various disasters. WMO played an active role in the activities of the ad hoc Panel on early warning systems established by the Committee on Science and Technology (CST) of the UNCCD. High on the recommendations of the Panel is the need to undertake a critical analysis of the performance of early warning, monitoring and assessment systems; the improvement of methods for and approaches to the prediction of drought and monitoring of desertification; and the development of mechanisms to facilitate an exchange of information focusing in particular on national and subregional networks. WMO's new major programme on Natural Disaster Prevention and Mitigation will provide the focus for the consolidation of its efforts in the area of early warnings and for taking new initiatives in this area in collaboration with other organizations.

8.3 Further enhancing climate prediction capability

Climate prediction capabilities are being enhanced through the Climate Variability (CLIVAR) project of the World Climate Research Programme (WCRP). The prediction of El Niño and the associated impacts are becoming possible, with reasonable skill, up to few seasons in advance. Related to this, WMO is broadening the implementation of the WMO Climate Information and Prediction Services (CLIPS) project, which is designed to promote the use of climate information and prediction services, capacity building, multi-disciplinary research and the development of new applications. Consensus long-range forecasts on droughts, which were issued at several Regional Climate Outlook Fora, organized in different parts of the world with active support from WMO, provide good early warning information to national authorities.

8.4 Assessing vulnerability and analyzing hazards

It is important to analyze vulnerability at the local, national and regional levels which is an important factor in evaluating the adequacy of early warnings. A good tool to assess those different vulnerabilities is the linkage between weather, climate and disaster databases to the different type of meteorological or hydrological disasters. In this regard, a pilot project is ongoing in Chile linking climate with flood disaster databases with the support of WMO through the World Climate Programme, as part of the activities of the Inter-Agency Task Force for Disaster Reduction (IATF's) Working Groups on Climate and Disasters and on Risk Vulnerability and Impact Assessment. This is an important tool for risk communication among policy makers and communities. WMO will continue to assist in developing and managing the relevant climate databases through data rescue and climate database management projects.

8.5 Implementing risk management applications

Risk management approaches need to be employed in combatting droughts and mitigating floods. In this context, hazard mapping, suitable agroclimatic zoning and the establishment of partnerships are essential tools for land use and preparedness planning. Several expert teams established by the Commission for Agricultural Meteorology (CAgM) of WMO are examining these issues critically and are issuing guidance reports for the users. In the area of flood forecasting and management, WMO's Hydrology and Water Resources Programme is implementing the Associated Programme for Flood Management (APFM) in collaboration with the Global Water Partnership, in the context of integrated water resources management. Several related projects are being developed in different parts of the world inorder to provide guidance on the development of support systems for sustainable land management and agroclimatic zoning.

8.6 Contributing actively to the implementation of the UN system' s International Strategy for Disaster Reduction (ISDR)

It is to be noted that society's ability to cope with and adapt to, climate change will depend heavily on its ability to assess how and where weather and climate patterns are likely to change, to predict the continuous fluctuations in risk and vulnerability to communities, and to develop adaptive strategies that will increase the community's resilience when the next potential disaster strikes. WMO leads the ISDR Working Group on Climate and Disasters.

8.7 Supporting the strengthening of the capabilities of the Parties and regional institutions with drought-related programmes

The capabilities of Parties and regional institutions with drought-related programmes will be strengthened and collaboration will be promoted with other institutions in drought- and desertification-prone regions, with emphasis on Africa, Asia, Latin

America and the Caribbean, and the northern Mediterranean region, which are all referred to in the Regional Annexes to the Convention. Examples of such institutions in Africa are the AGRHYMET Centre and the African Centre of Meteorological Applications for Development (ACMAD), both located in Niamey, Niger, the IGAD Climate Prediction and Applications Centre in Nairobi, Kenya and the SADC Drought Monitoring Centre in Gaborone, Botswana. In order to enhance capacity building in the development of National Action Plans within the framework of the Convention, WMO organized Roving Seminars on the Application of Climatic Data for Desertification Control, Drought Preparedness and Management of Sustainable Agriculture in Beijing, China in May 2001 and in Antigua and Barbuda in April 2004.

9 FUTURE PERSPECTIVES

The definition of land degradation adopted by UNCCD assigns a major importance to climatic factors contributing to land degradation, but there is no concerted effort at the global level to systematically monitor the impacts of different climatic factors on land degradation in different regions and for different classes of land degradation. Hence there is an urgent need to monitor the interactions between climate and land degradation. To better understand these interactions, it is also important to identify the sources and sinks of dryland carbon, aerosols and trace gases in drylands. This can be effectively done through regional climate monitoring networks. Such networks could also help enhance the application of seasonal climate forecasting for more effective dryland management.

There are serious gaps in the basic meteorological network and observational facilities in many areas, some of them in regions with severe land degradation problems. The most serious single and geographically widespread shortcoming is the lack of information on rainfall intensity. WMO is taking steps to facilitate the development of early warning systems by organizing the development of suitable instruments and statistical processing. Furthermore, WMO is coordinating efforts on the part of its Members to further investigations of using data from meteorological satellites to supplement knowledge of meteorological conditions influencing land degradation, especially over areas inadequately covered by ground-level observations. WMO, through its 188 Members, is pleased to be part of the effort to better understand the role of climate in land degradation and work with various national, regional and international organizations and the civil society in combating and arresting land degradation.

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Chapter

2

Afforestation for Restoration of Land and Climate Change Mitigation

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Chapter 2.1

Reforestation under climate change in temperate, water limited regions: current views and challenges

Csaba Mátyás

ABSTRACT

The ecological benefits of forests and afforestation at the sensitive lower edge of the closed forest belt (at the "xeric limits") are still disputed. Forests control erosion, dust storms and silting of streams but may reduce stream flow and reduce groundwater table level due to higher water use with consequences for water management. The forest/grassland transition zone is especially vulnerable to projected drastic temperature and precipitation shifts in the future. In spite of contrary expectations, the effect of forests and afforestation in improvement of regional climate conditions is restricted. Ecologically conscious forest policy and management requires the consideration of local conditions, of projections of future climatic conditions and also of non-forest alternatives of land use. The chapter investigates some of the relevant aspects of the ecological role of forests at the dryland edges on the example of three countries/regions on three continents.

1 INTRODUCTION

In the drought-threatened regions of the Eurasian and North American forest steppe[1] zone, reforestation and afforestation[2] has been long considered as crucial in rehabilitating of degraded, over-exploited lands, in stabilizing water supply, reducing desertification and in improving regional climatic conditions.

However, the generally positive effects of afforestation on regional climate and water resources are presently debated. Due to the limited understanding of interactions between physical processes and land cover, the dispute is still unresolved (Ellison et al. 2011), although the opinion prevails that in the forest steppe zone, water consumption of man-made forests might contribute to water scarcity and aridification, and may not achieve the goals of environmental protection (Jackson et al., 2005; Sun et al., 2006; Andréassian, 2004; Brown et al., 2005; Wang, Y. et al., 2008). Projected changes in global climate pose a further challenge on dryland ecosystems, as relatively small changes in the moisture balance may lead to considerable ecological shifts. Forests may even become a factor of increasing climate forcing (Drüszler et al., 2010; Gálos et al., 2011; Mátyás et al., 2009).

1.1 Climate, water and forests

Precipitation and temperature are the ultimate drivers of vegetation distribution on earth. Globally, zonal forests are generally found in areas where annual precipitation exceeds evapotranspiration, and thus forests are both dependent from and the sources of surface water resources. For example it is estimated that 50% of US water

1 Forest steppe is the transition zone to grasslands where (natural) forests largely depend on locally accessible surplus water

2 The terms afforestation and reforestation are used in this paper largely as synonyms. I.e. the question of original vegetation cover is left unconsidered, as it is difficult to assess it in landscapes under heavy human influence

supply comes from forest lands (Brown et al., 2008). Water use by temperate forests is generally less than 700 mm during the growing season, suggesting that ecosystem water use (tree transpiration + evaporation) is limited by energy and water availability (Sun et al., 2011a, Fig. 2). Analyzing temperate grassland and forest sites in the USA, Sun et al. (2011a) found that in the warm-temperate zone forests require at least 400 mm of precipitation in the growing season to sustain desired functions, and grassland and scrublands are found at sites where growing season precipitation is below 400 mm (Fig. 1). Interestingly, atmospheric precipitation was barely sufficient for most ecosystems among the 16 ecohydrological study sites in the USA, with only one exception in the humid subtropical region (Fig. 1).

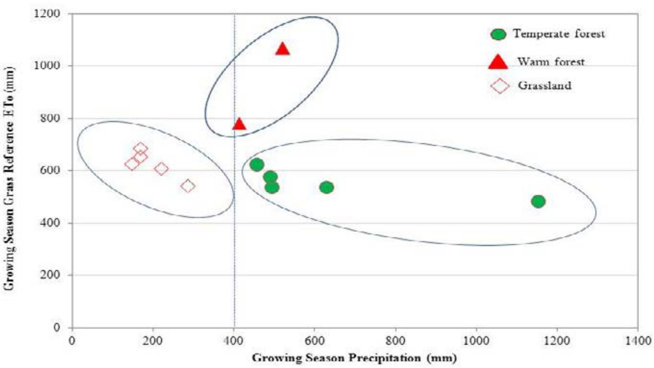

Figure 1. Growing season precipitation and grass reference evapotranspiration (i.e., P-ET) are major drivers for zonal vegetation distribution. Data are derived from an ecohydrological study with sites in the United States, China, and Australia. The figure shows grassland sites (cold steppes and milder-climate shrublands), poplar plantations where precipitation exceeds 400 mm (warm forests), respectively temperate forest sites (Sun et al., 2011a, Mátyás, Sun and Zhang 2013)

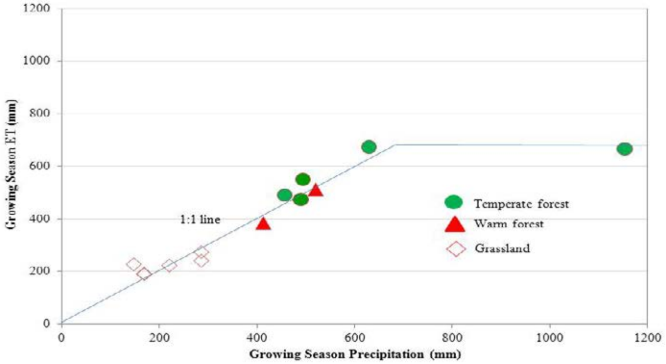

Figure 2. Water use (growing season evapotranspiration vs. precipitation) of grasslands and forests across ecohydrologic study sites (Mátyás, Sun and Zhang 2013)

2 EFFECTS OF FORESTS ON HYDROLOGICAL BALANCE IN DRY REGIONS

Compared to grasslands or short-cycle crops, forests have large above-ground biomass and deeper roots, therefore can use more water (Wang, Y. et al., 2011) and can capture larger amounts of carbon through photosynthesis as carbon and water cycles are highly coupled (Law et al., 2002; Sun et al., 2011b). World-wide vegetation manipulation experiments show that forest removals reduce water use, i.e., evapotranspiration (ET), and thus increase watershed stream flow. On the other hand, reforestation or afforestation on watersheds previously covered by native grassland can reduce stream flow due to an increase in ET (Andréassian, 2004). Forests have higher ET than harvested sites or croplands, so groundwater table levels are generally lower under forests (Sun et al., 2000, see also Fig. 3).

Earlier long-term forest hydrologic studies focused on deforestation effects, floods and sedimentation (Alila et al., 2009). Hydrologic studies on the consequences of afforestation have emerged in the past decade (Scott et al., 2005; Sun et al., 2006;

Wang, Y. et al., 2011). In particular, evaluation of worldwide reforestation campaigns has shown that human intervention requires a closer look at the unexpected consequences. An emerging question is how reforestation in different climatic regimes affects watershed functions such as water yield (Sun et al., 2006). The potential water yield reduction following afforestation for bioenergy development, ecological restoration, respectively for climate change mitigation, has drawn renewed attention to the relations between forests and water resources in watersheds (Calder, 2002; Brown et al., 2005; Jackson et al., 2005; Trabucco et al., 2008; Malmer et al., 2009) and on a regional scale (Ellison et al., 2011). The hot debate on 'planting' or 'not planting' policies is especially relevant in arid regions or regions with scarce water resources (Greeff, 2010).

2.1 China: landcover changes and effects on streamflow

Comprehensive forest hydrological studies that address forest-water relations did not start until the 1990s. Important findings emerged rapidly in the past two decades (Wei et al., 2008). In dry Northern China, such as the Loess Plateau region, empirical and modeling studies confirm that that forest vegetation and associated soil conservation engineering had significant influence on watershed stream flow (Zhang et al., 2008a; 2008b; Wang, Y. et al., 2011; Wang, S. et al., 2011).

Recent forest hydrology studies have detected that land cover and land use changes played a substantial role in stream flow reduction downstream (Zhang et al., 2008a; 2008b). A water balance modeling study suggests that if 5.8% and 10.1% of the study area on the Loess Plateau is planted with trees, stream flow will decrease by 5.5% and 9.2%, respectively. The rate of stream flow reduction decreased from dry to wet area in the Loess Plateau region (Zhang et al., 2008a). In another 40-year retrospective study (1959-1999), Zhang et al. (2008b) examined stream flow and climate data from 11 catchments in the Loess Plateau to investigate the response of stream flow to land use/cover changes. They found that all catchments had significant reductions in annual stream flow of -0.13 to -1.58 mm per year between 1971 and 1985. Land use/ cover changes accounted for over 50% of the reduction in mean annual stream flow in 8 out of the 11 catchments while in the remaining three watersheds precipitation and potential evaporation were more important. Among the soil conservation measures, construction of sediment-trapping dams and reservoirs, and the diversion for irrigation appeared to be the main cause of reduced stream flow.

To understand the effects of vegetation on stream flow in the Loess Plateau region, Wang, Y. et al. (2011) constructed multi-annual water balances for 57 basins to estimate annual evapotranspiration (ET) and runoff for forest lands and non-forest lands. The authors argue that large-scale afforestation may have serious consequences for water management and sustainable development in dry regions because of runoff reduction.

2.2 United States: effects of landcover management

Since the late 1930s, numerous 'paired watershed' studies have been conducted in the United States to examine forest management effects (harvesting with various intensities, species conversion, farming as an alternative), on water quality and yield across various climatic and topographic conditions (Ice and Stednick, 2004). In general, humid areas with high precipitation have higher hydrologic response in absolute terms, but dry areas with low water flow can have a higher relative response. For example, clear-cutting a deciduous forest in the humid south-eastern US, with an annual precipitation >1800 mm, can result in an increase in stream flow of 130-410 mm per year, which is 15-40% of undisturbed control watersheds, while the same management practice in the drier area of northern Arizona with an annual precipitation of 500-600 mm may result in a water yield increase of 60 mm or >40% of undisturbed control watersheds. Zou et al. (2009) summarized century-long vegetation manipulation experiment studies in the Colorado River Basin that provide a bounty of knowledge about effects of change in forest vegetation on stream flow in water-deficit areas. The watershed is situated at the headwaters of streams and rivers that supply much of the water to downstream users in the western United States. The authors found that vegetation can be managed to enhance annual water yields while still providing other ecological services. The effects of vegetation manipulation on stream flow are associated with the precipitation/elevation gradient and, therefore, with vegetation type. An annual water yield increase between 25 and 100 mm could be achieved by implementing vegetation manipulation in the high elevation subalpine and mixed conifer forests, the lower ponderosa pine forests and portions of the low elevation chaparral scrublands. The annual precipitation was generally above 500 mm in areas where a 100 mm increase in stream flow was achieved. Negligible or small increases in water yield were observed from treating sagebrush, pinyon-juniper woodlands and desert scrubs, with an annual precipitation below 500 mm. This study suggests that reforestation is likely to cause relatively larger hydrologic effect in areas where precipitation is roughly balanced by evapotranspiration demand, i.e., above 500 mm.

2.3 Hungary: reforestation and its effect on groundwater resources

In the last century, large-scale reforestation programs changed the land cover of the Hungarian Great Plain, with the aim to improve not only timber supply but also the regional climate and hydrology of the largely treeless landscape. For example, on the Danube-Tisza Sand Plateau, a region of 828 thousand ha, forest cover increased in four decades from 5 to 26%. A debate between hydrologists and foresters about the true effects of reforestation led to numerous studies to investigate effects of forest cover on water resources.

Measurements confirmed that in areas where deep rooting forests can tap the groundwater, the evapotranspiration (ET) rate surpasses the amount of precipitation. On the Sand Plateau, with an average annual precipitation of 526 mm, ET was estimated from MODIS daytime land surface temperature data. Average annual ET of forests was estimated at 620 mm a^{-1}, which was about 80 mm more than the actual annual precipitation (Szilágyi et al. 2012). In a black pine plantation a mean annual ET rate of 712 mm a^{-1} was registered by Major (2002) out of which 130 mm originated from the groundwater.

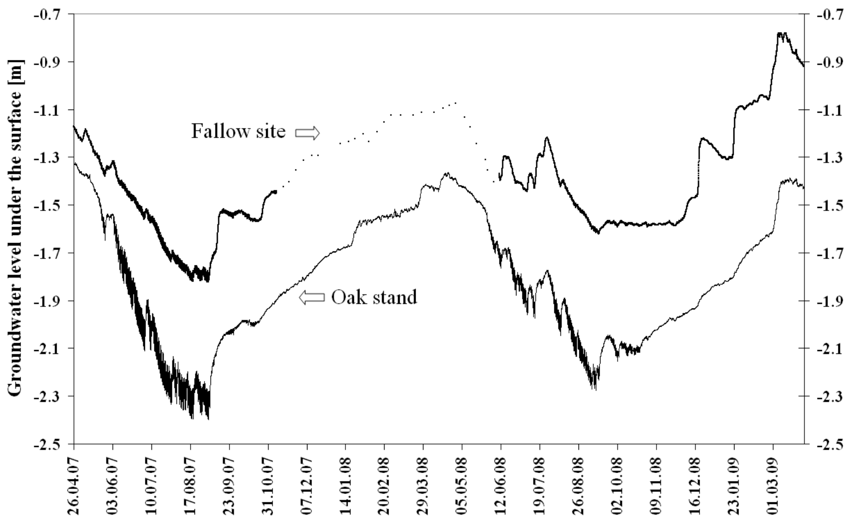

Figure 3. Water table fluctuation in the course of one year under an oak forest (Quercus robur) and a neighboring grassland (fallow) site in the forest steppe zone of Hungary (design: N. Móricz in: Mátyás, Sun and Zhang 2013)

In other studies the groundwater consumption of forest and of grassland was compared. In a somewhat less harsh climatic environment of 570 mm annual rainfall and a growing season precipitation of 360 mm (i.e. still a potential grassland climate according to Sun et al. 2011a), an oak forest had approx. 30% more annual evapotranspiration than a neighboring fallow (405 vs. 283 mm). The difference was however much higher in average groundwater use (oak: 243 mm, fallow: 85 mm). The groundwater consumption was close to 60% of the total transpiration of the oak forest and approximately 30% of the fallow. Groundwater consumption was approximately 40% less in a wet than in a dry growing season, despite the fact that the groundwater table was deeper during the dry period (Móricz et al. 2012).

Various measurements have shown that in shallow groundwater areas on the Danube-Tisza Sand Plateau forest vegetation may lower water table from 0.5 up to 1.1 m compared to the level below herbaceous vegetation (Major 2002). Under natural conditions, if maximum groundwater level (in April) is deeper than -2.5 m, grassland predominates in this climate.

Measurements revealed that in the Hungarian forest steppe climate zone, forest cover does not contribute to groundwater recharge or to runoff, and utilizes additional, near-surface groundwater resources. Due to lower groundwater levels under forests, local water table depressions develop, which may direct groundwater flow toward forested patches.

3 THE CHALLENGE OF CHANGING CLIMATE

3.1 The climatic transition zone at the forest/grassland edge

The climatic and biogeographic conditions of the continental plains of South-eastern Europe and of temperate Northeast Asia are very diverse, which is also true for their socio-economic statuses and current problems (i.e. land use change, soil degradation or desertification). What makes this region specific is the presence of the so-called *xeric limit* of forests and forest tree species.

Xeric (or rear, trailing[3]) forest limits are at the low latitude, low altitude end of distribution ranges of temperate forest trees, where presence or absence of (climate-) zonal, closed forests is determined by climatic aridity (Mátyás et al., 2009). Xeric limits appear in low-precipitation zones of continental plains, along the foothills of mountain ranges, and at the edges of dry basins in the temperate-continental climate. At the xeric limit, the closed forest belt forms a transition zone (ecotone) toward the open woodland or forest steppe, which dissolves with decreasing precipitation into the true steppe or grassland. The forest/grassland ecotone is dependent on a volatile minimum of rainfall and is therefore sensitive to prolonged droughts. The physical characteristics of the land surface (e.g., albedo, evapotranspiration, roughness etc.) as well as carbon cycle and ecological services are strongly affected by land use policy and changes in this area.

The forest steppe belt reaches from the plains of Southeast Europe and South Russia into Southern Siberia and North China. Temperate xeric limits exist also on other continents, along the edge of the Prairies of North America, notably from the southwest states of the USA northward into Alberta (Canada). In Southeast Europe, and also in China the transition zone is a densely populated and is an agriculturally important region which has been under human influence for millennia. On flat terrain, the climatic transition from closed forests to grassland is difficult to trace, due to variability of hydrological conditions and, first of all, due to strong human interference.

Forest ecologists in Eastern Europe distinguish a specific forest steppe (woodland) climate. According to Hungarian data, the zone classified into this category is characterized by an average precipitation of 563 mm per year, a July mean of 21,5 °C and a water deficit of 346 mm (Mátyás and Czimber 2000). Scarce precipitation in the vegetation period (approximately 320 mm) and frequent summer droughts limit the presence of closed forests except to sites where supplementary water resources are available below ground. Forest crown interception and litter interception may further diminish available water resources even in more humid forested catchments (Gribovszki et al 2006). In forest steppe climate, loss through crown and litter interception can be up to 25-40%. Native, deciduous species have generally values under 30%, whereas conifer plantations intercept between 35 and 40% of the already meager precipitation (Járó 1980). Natural forest cover remains therefore patchy in this zone, indicating mosaics where groundwater influence improves site conditions.

3 The terms in brackets refer to events of postglacial migration, where xeric limits represent the "rear" end of shifting vegetation zones, triggered by gradual warming

3.2 The climatic vulnerability of the forest/grassland transition zone

The forest-grassland transition zone is especially vulnerable to expected climatic changes in flat lands because of the magnitude of the *latitudinal lapse rate*. It is generally known that the altitudinal lapse rate for temperature (i.e., the rate of change with increasing elevation) is 5.0 - 6.5 °C/1000 m. The latitudinal (south to north) lapse rate is less recognized. In the temperate zone its mean value is around 6.9 °C/1000 km - a difference of three magnitudes. This means that predicted changes of temperature affect disproportionately larger tracts of plains as compared to mountainous regions. A temperature increase of only +1 °C causes a shift upwards along a mountain slope of approximately 170 m. On a plain, the same change triggers a shift of close to 150 km (Jump et al., 2009). This explains the much greater vulnerability of rain-dependent vegetation on plains. Predicted changes may easily trigger the loss of already sparse forest cover, which may lead to the disruption of vital ecological services that the forests provide.

3.3 Recently observed climatic impacts

Across the temperate zone, a relatively rapid increase of annual mean temperature has been observed in recent decades, and the dryland zone in China and Mongolia is no exception. In the last half century, both average temperatures and climatic extremes increased (Qi et al., 2012). For instance, average temperatures in Mongolia increased by more than 2 °C since 1940 and nine out of the ten warmest years occurred after 1990 (Lu et al., 2009). In North China, frequency of droughts intensified during the past several decades, leading to an unprecedented increase of dry areas (Piao et al., 2010). Growing season anomalies have been generally increasing in China in the 2000s: drought events got significantly stronger in North China and soil moisture declined (Zhao and Running, 2010).

Numerous studies and also IPCC's 2007 report forecast a decline in growth and production of forests in dry regions. At the same time, analyses of impacts of climate on forests are limited or sporadic. For instance, FAO global statistics do not yet calculate with the effect of forest cover loss due to aridification (FAO, 2010). There are reports about observed impacts from western North America (Allen et al., 2010; Hogg and Price, 2000), while impacts in Eastern Europe, Central Asia and the Chinese Drylands are less known (Zhang et al., 2008b; Piao et al., 2010; Mátyás, 2010a). It should be noted, however, that the reason for the missing evidence for impacts of gradually worsening ecological conditions has to be sought probably in improper data analysis. Specific experiments on growth and yield confirm the expected negative impact of rising temperatures on vitality and survival (Mátyás et al., 2010; Fig. 4).

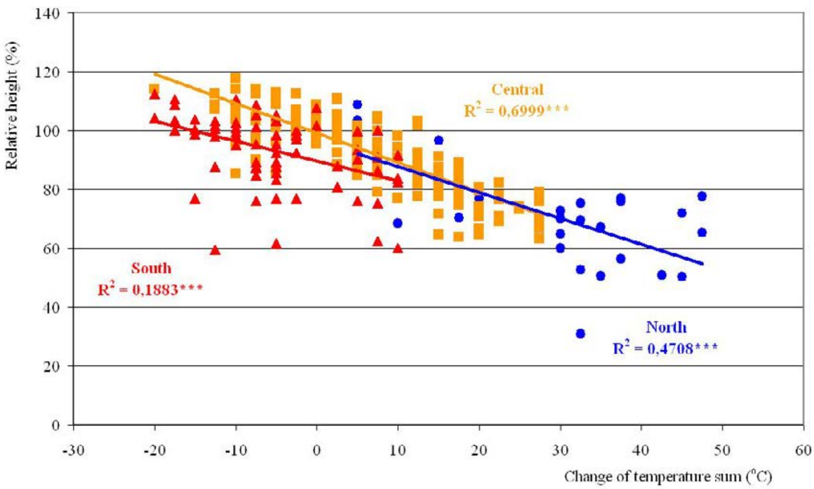

Figure 4. Growth response of geographically transferred Scots pine (Pinus sylvestris) populations (provenances) to simulated warming. The increase of annual temperature sum (in °C degree-days) resulted in a decline of relative height irrespective of origin (central, northern or southern populations). Re-analyzed data of six Russian experiments (Mátyás et al. 2010, Mátyás, Sun and Zhang 2013).

3.4 The hidden threat at the xeric limits: increasing drought

According to calculations of IPCC, projected temperature changes of the critical summer climate at the end of the century are more drastic in the forest/grassland transition zone than in the boreal zone of Eurasia. Projected summer precipitation decline and shifts in drought frequency is of special significance at the xeric limits which are extremely sensitive to even minor humidity variations. Mass mortality may appear, especially on sites with unfavourable water regime.

3.5 Considerations for forest management

In most temperate zone countries with drylands, instead of large scale afforestation with plantations, returning to close-to-nature forest management seems to be the general trend to mitigate impacts of environmental change (e.g. Xu 2011, see also Mátyás 2010a). The concept is based on the hypothesis that stability and persistence of forest ecosystems is warranted by plant communities having evolved during the past millennia, and enhancing the naturalness of forests will also enhance their stability. The hypothesis is challenged at the xeric limits by numerous constraints, such as

- long-lasting human interference and land use have caused a partial or total loss of natural (woody) plant cover, spontaneous processes of vegetation recovering might be very slow,
- number of native species expected to tolerate expected environmental changes is usually low,
- functioning of close-to-natural systems is disturbed by indirect human effects (e.g., grazing and game damages, air pollution) and by the projected climatic changes and extreme events.

These constraints necessitate a considerate revision of the commitment to naturalness, first of all in regions of high drought risk. It is believed that carefully planned and active human interference is unavoidable in dry lands because the long-term ecological and genetic effects of adaptation to environmental changes have to be considered.

A cost-effective, scientifically based forest policy in the forest steppe zone requires the consideration of local environmental conditions, of land use alternatives such as restoration of grasslands and scrublands, and the use of the proper technology. Experiences from the United States confirm that vegetation can be successfully managed to enhance annual water yields while still providing other ecological benefits. Carefully planned human interference is therefore essential, to achieve a successful policy of restoration and of adaptation to the expected environmental changes.

4 SUMMARY AND CONCLUSIONS

Current views and experiences about the role of forests at dryland margins are contradictory. Although forests provide multiple ecological benefits, reforestation or afforestation on watersheds previously used by agriculture or covered by grassland can reduce stream flow due to higher water use and may have serious for water management and sustainable development. In the forest steppe climate zone, forest cover does not contribute to groundwater recharge or to runoff, and utilizes near-surface groundwater resources.

Forest cover influences atmospheric climate forcing. Therefore it is believed that forests mitigate climate change impacts such as warming and aridification. Studies indicate that in spite of increased evapotranspiration, precipitation changes are only moderately even in extensively afforested regions. At the same time, the lower albedo of forests may even lead to minor temperature rise. It seems that the balance between albedo and actual evapotranspiration determines whether there is a cooling or warming effect.

The forest/grassland ecotone is dependent on a volatile minimum of rainfall and is therefore sensitive to climatic changes. Projected summer precipitation decline and shifts in drought frequency may easily trigger the loss of forest cover, which may lead to the disruption of vital ecological services that the forests provide. Because of the extreme long-term character of forestry, the consideration of projected future climate effects has to play a central role in management planning. Stability and growth of forests depend on humidity conditions of the future especially in the dryland transition zone. Concerns about hydrology and climate should be weighed when making decisions about land use changes. Studies confirm that proper forest management and associated soil conservation engineering have a beneficial influence on ecology of watersheds.

RELATED WEBSITES, PROJECTS AND VIDEOS

climatic role of forests: http://www.youtube.com/watch?v=fwpfbDfKDMU

Land Use, Land Use Change and Forestry (LULUCF): http://forest.jrc.ec.europa.eu/activities/lu-lucf/

Northern Eurasia Earth Science Partnership Initiative (NEESPI): http://neespi.org/

MARGINS project: http://margins.ecoclimatology.com/index.html

Expected climate change and options for EU silviculture (ECHOES): http://www.forestry.gov.uk/website/forestresearch.nsf/ByUnique/INFD-7NBCPQ

EU targets action on forests: http://www.euractiv.com/sustainability/eu-targets-action-forests-news-299524

EU Green Paper on forest protection and climate change: http://www.euractiv.com/sustainability/eu-targets-action-forests-news-299524

IPCC AR4: Forestry: http://www.ipcc.ch/publications_and_data/ar4/wg3/en/ch9.html

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Chapter 2.2

Forests in a changing climate

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ABSTRACT

This chapter provides quantitative information on the effect of climatic change on the distribution, growth, health and vitality of forests. In the analyses European beech is selected as indicator species. Although it is considered in its optimum highly plastic and adaptable, it becomes climate-sensitive closer to its xeric (lower) distribution limits. The future of beech in Southeast Europe requires special attention because this region harbours significant populations living at or near their xeric distribution boundary. Even though the low elevation occurrences are uniquely vulnerable to climatic shifts, observations and modelling studies pertaining to this region are particularly scarce.

Out of climatic factors determining the xeric distributional limits for beech, Ellenberg's drought index (EQ) appeared as the most influential. Growth response analyses in comparative tests have confirmed the existence of macroclimatic adaptationof beech and have proven that warming and more arid conditions lead to decline of growth and vitality, while no decline was observed if EQ changed in the opposite direction. The response to weather extremes was investigated in field plots. Recurrent summer droughts of 3 to 4 consecutive years, above mean EQ value 40-42 resulted in pest and disease attacks and mass mortality.

The discussed approaches indicate consistently a high level of uncertainty regarding the future of beech at the xeric limit in Southeast Europe. According to field observations and bioclimatic data in Hungary, a large part of low-elevation beech forests presently in the zone of EQindex ≥20 might be threatened by the warming in the second half of the century, while higher-elevation occurrences

may remain stable. The interpretation of the results bears some stipulations, such as the consequence of ecological and human interactions in influencing present distribution patterns, the unclear role of persistence, natural selection and plasticity and uncertainties of climate projections. Grim projections may probably be partly overwritten by the mentioned stipulations and by careful and prudent human support.

1 CHANGES IN CLIMATE CONDITIONS WITH RESPECT TO FOREST ECOLOGY

Adaptation strategy of forest trees is receiving growing attention in view of expected climatic changes. Scarcity of reliable information on responses to macroclimatic changes is a central problem and obstacle of planning for the future. Inorder to formulate realistic predictions, both the nature of adaptation to past and current climate, and the level of sensitivity to sudden environmental changes have to be understood and properly interpreted. The distribution of European beech extends across ecologically and climatically variable regions. Compared to other wide-spread tree speciesof Europe, it is still the one which was left in a relatively natural condition as – although in a distributional range reduced by man – it was seldom regenerated artificially and its reproductive material was not subject to large-scale commercial relocations such as oaks or Scots pine. Thus, present populations of European beech are still close to a „wild state". Therefore beech is a well suited model species to study adaptation strategy of long-living, deciduous climax species to climate and to changes of climate. The species is considered climate-sensitive and vulnerable to changes. Therefore its response to predicted large-scale changes of climate is a critical issue.

In this study an attempt is presented to trace, quantify and project the impacts of macroclimatic change on the distribution and vitality of beech, with results interpretable for the practice, as such information is urgently needed to develop adaptation strategies for both forestry and conservation. Investigations were concentrated to the xeric limits in SE Europe. This region, where the retreat of the species is imminent, has been largely neglected by European studies (Jump et al. 2009, Mátyás et al. 2010). We consider the detailed, practice-oriented investigation of climate impacts at the xeric limits of primary importance because especially the low elevation occurrences of beech in the region are uniquely vulnerable to climatic shifts (Mátyás et al. 2010).

1.1 The threat to xeric limits in SE Europe

Xeric (or rear, trailing) limits at the low latitude and low altitude end of distribution ranges are determined by climatic aridity (Mátyás et al. 2009). At the xeric limit ecosystems are dependent on a volatile minimum of rainfall and are therefore sensitive to prolonged droughts. Even minor changes of temperature affect disproportionately larger tracts on plains as compared to mountainous regions. Presuming a spontaneous migration speed for beech of approx. 20 km/century (Davis 1981, Mátyás 2007) an increaseof temperature of just 1°C would imply for beech a horizontal migration time of 750 years to follow the change. This fact explains the much larger vulnerability of low elevation occurrences in Southeast Europe.

According to calculations of the IPCC (Christensen et al. 2007), predicted temperature changes of the critical summer climate at the end of the century are much milder in North Europe between latitude 50° and 70° N, as compared to South Europe between 50° and 30° N. Table 1 shows that changes are more extreme in summer than those of annual averages. Drought projections for Southern Europe are also serious, while none are predicted for North Europe.

Table 1. Predicted annual and summer climate changes for the period 2080-2099 vs. the reference period of 1980-1999, according to the A1Bscenario (data from the IPCC, Christensen et al. 2007)

	mean annual temperature dT (°C)	mean summer temperature dT (°C)	Change of mean annual precipitation dP (%)	mean summer precipitation dP (%)	percentage of dry summers (%)
South Europe, Mediterranean	+3.5	**+4.1**	- 12	**- 24**	**42**
North Europe	+3.2	**+2.7**	+ 9	**+ 2**	**0**

The expected drought frequency was separately modelled by us for the Carpathian Basin due to the importance of this climate factor (Gáloset al. 2007). The results of the projection, using the regional climate model REMO developed by the Max Planck Institute for Meteorology (Hamburg) indicate a very similar outcome: in the second half of the 21st century every second year could bring major summer drought events

(Table 2). Projected summer precipitation change is of special significance at the xeric limits which may affect profoundly the available climatic niche of dominant forest species, such as beech. This justifies the separate treatment of the Southeast European region.

Table 2. Frequency of recent and projected drought events for Hungary, according to scenario A1B, calculated with MPI's REMO regional climate model. Reference period: 1961-1990 (Gálos et al. 2007)

Period	Drought summers		
	number of years (out of 50 years)	mean of precipitation anomalies (%)	mean of temperature anomalies (°C)
1951–2000	15	–28.0	+0.9
2001–2050	17	–19.8	+1.5
2051–2100	26	–37.6	+4.2

1.2 Climatic factors of the xeric distributional limits for beech in SE Europe

The actual climatic envelope (niche) of beech has been repeatedly modelled (e.g. Kölling 2007, Bolte et al. 2007, Kramer et al. 2010). However, the studies focus on continental-scale effects of climate change, using low resolution climatic and species distribution data. To identify the limiting macroclimatic factors at the xeric distributional limits of beech forests a regional modelling analysis was carried out in Hungary (Czúcz et al. 2011). Out of the basic set of climatic variables late spring (May) temperature (T05) appeared as the most influential predictor. In addition, annualprecipitation (Pa) also played a significant role in determining the presence of beech near its xeric limit (Czúcz et al. 2011).

The probability of presence of beech was modelled by the variables seasonal and monthly temperature and precipitation means, interpolated for the grid cells. In addition Ellenberg's climate quotient (EQ, Ellenberg, 1988) was also applied, defined as themean temperature of the warmest month (July, T07) divided by annual precipitation (Pa):

$$EQ = 1000\ (T_{07} / P_a)$$

Ellenberg's climate quotient is a simple index expressing the joint effect of temperature and precipitation, and it has been generally used to express humidity conditions in Central Europe.

It is obvious that when modelling the probability of presence of beech, neither temperature nor precipitation can be considered as a single factor. EQ index seems to characterise the climate conditions for beech in the region reliably and will be used for analysing responses to changing conditions in the followings.

2 GROWTH RESPONSE TO CHANGING CLIMATIC CONDITIONS

The growth response (or transfer) analysis of the SE European beech trials yielded the following main conclusions (Mátyás et al. 2010):

- a climate-dependent component of adaptive genetic response could be identified
- across populations of different origin, i.e. adaptation to (and consequently, selection effect of) macroclimate exists in beech in spite of counteracting evolutionary and ecological effects;
- the change of climatic conditions toward warming and more arid conditions lead to decreasing height growth and vitality, while vitality is not affected if changes happen in the opposite direction.

3 RESPONSE TO WEATHER EXTREMES

Effects of climatic change are described as shifts of vegetation zones, realised through "migration" of species. In case of forest trees, "migration" means loss of competitive potential and subsequent decline of vitality followed by pestand disease attack. However, the response of forests to drought – contrary to grass or crop vegetation – is not immediate. Forest stands, even drought-sensitive beech, survive single extreme summers and recover merely with yield loss. This is the result of deep rooting of trees, utilizing deeper soil water resources. The situation is different if drought years happen consecutively.

In the literature "mortality syndrome" (Worrall et al. 2008) cases have mostly been treated as isolated, transient problems related to extreme events, rather than as a consequence of a long-term climate shift. This is because the gradual, relatively slow change of climatic means does not express the current effect of extremes at the xeric limits. Spontaneous climatic selection is driven by recurrent drought eventsand the symptoms of change appear usually quite abruptly. Climatic means in models should be regarded therefore rather as surrogates for extreme events. The long-term, gradual shift of climatic factors has merely predisposingrole. Besides climate, the site conditions, age andstructure of stand play also a predisposing role. Incitingfactors are mainly connected to climatic anomalies especiallyat the xeric limits. Pests or diseases attacking populations of weakenedvitality are then the direct or proximate causes of mortality.

3.1 Health and vitality loss due to climatic extremes: case study of beech in SW Hungary

The gradually growing moisture deficit in Hungary has led to health problems in Hungarian beech forests since the 1990s, first of all in the Southwest of the country where climatic changes were the strongest, and where the stands are at low elevation and close to the xeric limits. The weakened trees became more sensitive to secondary pests and pathogens and showed symptoms of health deterioration (early leafabscission, sparser crowns, etc.). The extent of climate damages of the drought years 2000–2004 has been investigated in two West Hungarian state forest companies. In 460 damaged forest compartments (total area: 3900 ha) 87.7 thousand cu.m. of damaged timber was harvested. The damaged stands were mostly above 60 years (T. Szép, unpubl. data). The area most damaged was the Zalaegerszeg forest district (Zala county), where mass mortality was triggered in mature beech stands after regeneration cuts, when the canopy closure was opened up. This led to the outbreak of the otherwise harmless beech buprestid (Agrilus viridis). Damage of Biscogniauxia nummulariadisease and of the beech bark beetle (Taphrorychus bicolor) occurred together with the buprestid damage. As a consequence close to 70,000 cu.m. of sanitary felling had to be executed in 2005 in that forestry district alone (Figure 1, Lakatos – Molnár 2009). The type of damage supports the observation of forest protection experts that disturbance of the closed canopy increases the risk of climate damage.

Figure 1. Symptoms of beech decline in 2004 in Zala county, following the damage of Taphrorychus bicolor on thetrunk (Molnár – Lakatos 2009)

3.2 Analysis of drought events

For the closer definition of extreme weather effects leading to the "mortality syndrome" in beech, threatened stands have been selected in different parts of the country. For the analysis on annual basis, EQ had to be modified to be suitable to characterise individual years' weather. Mean temperature of the 3 summer months was used for the annual EQ index instead of just July's, to avoid random effects of individual months (in case of 30-year climate averages, this is not a problem). Investigation of mortality frequency has shown that single drought events did not threaten the stability of populations. The recurrent drought period lasting up to five years in some areas, has however resulted in very serious mortality in the investigated beech stands, in one case the population went extinct (Figure 2).

As an example, effects of consecutive drought events are shown for a South Hungarian beech forest at the xeric limits of distribution. The stand has been selected at the edge of the xeric limit which is indicated by the frequency of droughty years. Years with EQ indices significantly above 30 have been considered as drought events. Mass mortality started in 2003, in the fourth year of consecutive drought, after an extremely dry summer. Observations at other locations have confirmed thatin case of beech, recurrent drought events of 3 to 4 consecutive years (depending on severity) lead in general to irreversible mass mortality and local extinction (Berki et al. 2009). It was also found that not only the number of consecutive years, but the severity of drought period has an influence on the decline. Data of selected observation plots near the xeric limit (Figure 3) confirm a direct, causal link between health and drought. Mean summer drought severity above EQ value 40–42 seem to trigger a mass mortality syndrome.

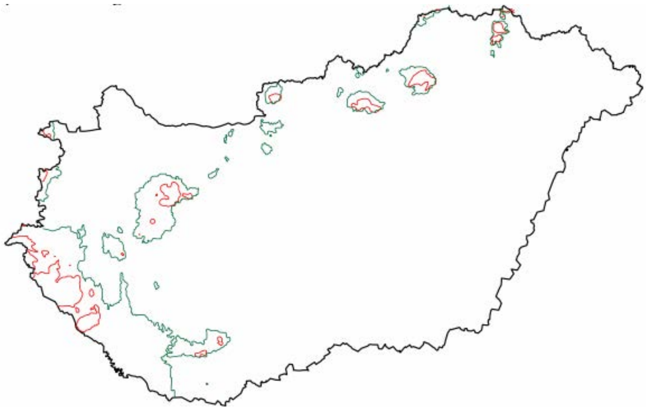

Figure 2. Shrinking of the climatic xeric limit ofbeech (EQ = 29) in Hungary between the beginning of the 20th century (1900-1930, green) and for the period 1975-2004 (red). (design: E. Rasztovits)

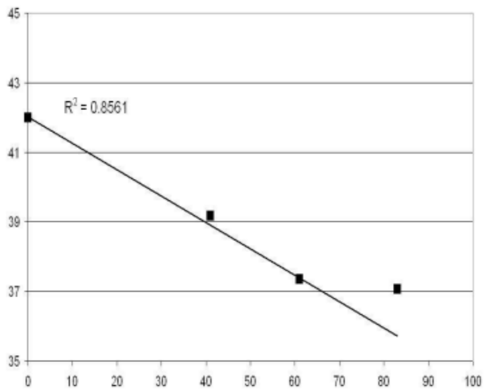

Figure 3. Average EQ value of the drought years 2000-2004 (vertical axis) and the health condition of selected mature beech plots at the xeric limit, at the end of the period (percentage of healthy individuals, horizontal axis) (unpublished data of Berki and Móricz)

4 PROJECTIONS FOR THE FUTURE

How exactly xeric limits of beech will shift in the future is poorly explained by currently available models. For predicting future distribution of beech on the basis of bioclimatic models, climatic projections of the Intergovernmental Panel on Climate Change (IPCC, Christensen et al. 2007) were applied (Table 3).

Table 3. Expected changes of climatic conditions by 2050 and estimated climatic space of zonal beech (Δbeech) forest stands in Hungary. Projected changes in summer half year temperature (ΔTs °C) and precipitation (ΔPs, percents) are shown for six IPCC AR4 climatic scenarios (extracted from Czúcz et al.2011)

	HADCM3 A2	HADCM3 A1B	HADCM3 B1	CNCM3 A2	CSMK3 A2	GFCM21 A2
ΔTs	+2.9	+3.3	+2.6	+2.4	+1.8	+2.1
ΔPs (%)	–13.4	–10.9	–12.4	–9.6	+ 0.4	–11.4
Δbeech (%)	97–99	94–99	97–99	97–99	56–96	92–99

Table 3 reveals surprisingly high levels of range reduction, relatively independently from applied scenario projections. The projected potential distributions indicate a drastic reduction in macroclimatically suitable sites for beech, as 56–99% of present-day zonal beech forests might be outside their optimal bioclimatic niche by 2050. However, the projections of analysis only pertain to zonal beech forests in plachor position and other uncertainties of the projections are also high (Czúcz et al. 2011).

Climatic changes will result in relatively homogeneous shifts in EQ values throughout the SE European distributional range of beech. Using the projected statistics of IPCC for Southern Europe (partly presented in Table 1), the climatic shift until 2080 was calculated as +11 ΔEQ. This suggests that – using the distribution limit value of 29 EQ – at locations with present EQ values below 29 – 11 ≈18~20 EQ, beech may survive, even if under stress. The larger part of the distributional range, especially Atlantic NW Europe as well as the higher elevation occurrences of the continental mountains (e.g. the Carpathians or the Balkan Range), fall into this group.

On the contrary, at the low-elevation xeric limits EQwould rise in 2080 from 29 to 40 EQ. Theoretically, part of these populations could survive as well, assuming that mass mortality starts only if the difference from the originally adapted climate surpasses +13 ΔEQ as stated above – if no extreme events and subsequent pests, epidemics occur in this time period. This assumption seems rather unrealistic. It has to be emphasized that all modelled responses were measured within the present distribution range of beech; there is no test site outside the xeric limits (which is a deplorable, but understandable drawback of the provenance test series). It is therefore impossibleto formulate a more realistic estimate based on transfer analysis for the locations close to thelimits.

4.1 Responses validated by field observations

The future frequency of drought events has been analysed for the territory of Hungary. The projected frequency of drought summers (precipitation decline exceeding 15% of the seasonal mean) were calculated with MPI's REMO regional climate model (Figure 9). It is highly remarkable that from 2050 onward, the model projects at least one occasion per decade when 3 or more consecutive years with drought summers will happen, while only three such periods are projected for the first half of the century. Although droughts hit usually regionally, the predicted drought frequency may have an impact on the most part of the investigated beech area at least once during the century. The close link between extreme events and pest outbreaks exacerbate the expected damages. Drought will have its effect also on natural regeneration of stands as well (Czajkowski et al. 2005). These results support the grim outcome of the bioclimatic forecast for the second half of the century.

Figure 4. Frequency of consecutive drought events for Hungary, according to scenario A1B, based on results of the REMO model. Symbols depict years of droughty summers (Gálos et al. 2007)

Concluding, the outcome of the projections indicates a high level of uncertainty regarding the future of beech in Southeast Europe. **According to the bioclimate approach 56–99% of present-day zonal beech forests might be outside their optimal climatic niche by 2050** (figure 5). **The extrapolations of field observations on "drought plots" at the xeric limit also point toward a nearly complete loss of all beech stands in course of the century.**

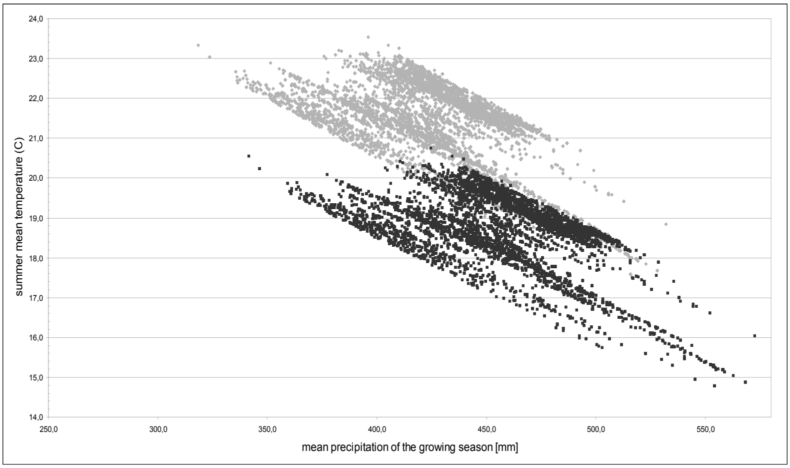

Figure 5. Climate parameters (mean precipitation of the growing season vs. mean summer temperature) of actual beech occurrences in Hungary (black) and parameters calculated for the climate conditions in 2050 (grey) (data by E. Rasztovits)

5 FINAL CONCLUSIONS

Summing it up, projections into the far future may be biased by a number of uncertainties. Taking the ensemble of deductions of current, fairly deviating projections for granted, the comparison of very different approaches confirm the probability of serious climate impacts on distribution, health and productivity of beech. These effects will appear nonetheless differentiated, according to theecological and genetic status of local beech occurrences. It is also important to note that contrary to mortality events and health decline along the xeric limits of the species, "compensatory" colonisation at the thermic (or front) limits, as projected by ecological models, will not happen spontaneously because of human obstacles to colonisation and due to the fairly lowmigration speed of beech compared to other deciduous species (Davis 1981, Mátyás 2009, Jump et al. 2009).

Observations of mortality events close to the lower (xeric) limit of the species indicate that **stability and vitality of populations depend not only on shifts in climatic means. Extreme weather events (droughts) may weaken physiological condition of populations relatively fast and may lead to insect and disease outbreaks also in regions generally suitable for the species.** The shrinking of future distribution of beech as suggested by various bioclimatic models (e.g. Thuiller et al. 2005, Czúcz et al. 2011) represent probably pessimistic scenarios which may be alleviated not only by the mentioned features but also by prudent human support (e.g. artificial regeneration and other silvicultural measures, see Mátyás 2010). In the major part of the range the predicted changes will not trigger any decline due to the plasticity of the species: the predicted "decoupling" is improbable (Jump, Penuelas 2005). It would be however misleading to expect the same level of persistence and plasticity at the threatened xeric limits as across the rest of the range.

Therefore the forecasts have to be taken serious close to the xeric limits, and especially at low elevations. Field observations near the retracting distributional limits confirm that the decline process is ongoing in many locations (Penuelas et al. 2007, Berki et al. 2009). Considering the rapid shrinking of suitable bioclimatic space and the increasing selection pressure of abiotic and biotic stressors at the xeric limits, the results underline the importance of adaptive strategies both for management and conservation of forest resources. This calls also for relevant, well designed field studies and further development of prediction methods and modelling (Mátyás 2010).

The results of this study may contribute to the adjustment of adaptation and mitigation policy in forestry and nature conservation, to the revision of rules for deployment of reproductive material and also to validating evolutionary and ecological hypotheses related to climate change effects.

5.1 Related websites, projects and videos

Forest cover maps, forest type maps for Europe:

http://forest.jrc.ec.europa.eu/activities/forest-mapping/

http://forest.jrc.ec.europa.eu/efdac/applications/viewer/

http://www.euforgen.org/distribution_maps.html

forests and climate change (on maps): http://forest.jrc.ec.europa.eu/activities/climate-change/

climate change impacts on forestry: http://www.forestry.gov.uk/fr/INFD-5Y2HR7

IPCC AR4: Forestry: http://www.ipcc.ch/publications_and_data/ar4/wg3/en/ch9.html

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Chapter 2.3

Afforestation for Restoration of Land and Climate Change Mitigation, Part 3.

Structure and functioning of forest ecosystems

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Csaba Mátyás

1 Forest microclimate and microclimate measuring techniques

1.1 Introduction

Microclimatology is the study of climate on a small scale, as of a city, a valley, but even a hole in the tree trunk has its own microclimate. The microclimate of the forest is one of the most complicated amongst other land cover forms. The reasons for complexity are the levelled structure, the annual variability and the fact that not only the climate influences the forest, but the forest also affects its own microclimate. This dynamic feedback makes the description and modelling of the forest microclimate more difficult. Proper understanding of the main micrometeorological processes is vital for effective forest planning and management. Thus firstly we will cover the basics of micrometeorology, the structure of the boundary layer and the exchange of energy and water. Typical microclimatological situations such as land-sea and mountain-valley circulations and local cold airflows are analysed. Forests have a certain vertical structure, which further complicates the processes. During the vegetation period the canopy is the active surface for the energy transformation, and the trunk space may have highly different microclimate depending on the horizontal structure. By changing the density and distribution of the canopy, forest managers have a flexible tool for helping regeneration and the growth of seedlings. Lastly basic microclimatological measurement techniques are discussed.

1.2 Syllabus

1.2.1 Micrometeorology

Chapter 1.1 (pp. 1-4) in Foken (2008): Micrometeorology

a) **Atmospheric scales**

Chapter 1.2 (pp. 4-5) in Foken (2008): Micrometeorology

b) **Atmospheric boundary layer**

Chapter 1.3 (pp. 6-8) in Foken (2008): Micrometeorology

c) **Energy balance**

Chapter 1.4 (pp. 8-23) in Foken (2008): Micrometeorology

d) **Water balance**

Chapter 1.5 (pp. 23-24) in Foken (2008): Micrometeorology

1.2.2 Basics of microclimatology

a) **Climatological scales**

Chapter 7.1 (pp. 223-224) in Thomas Foken (2008): Micrometeorology

b) **Small scale changes of climate elements**

Chapter 7.2 (pp. 224-225) in Foken (2008): Micrometeorology

c) **Typical microclimatic circulations**

Chapter 7.3 & 7.4 (pp. 226-230) in Foken (2008): Micrometeorology

1.2.3 Forest Microclimate

a) **Vertical structure of the forest**

Parker (1995): Structure and microclimate of forest canopies

b) Horizontal microclimate gradients

Davies-Colley et al. (2000): Microclimate gradients across a forest edge

c) Effects of different management regimes

Chen et al. (1999): Microclimate in Forest Ecosystem and Landscape Ecology

Zheng et al. (2000): Effects of silvicultural treatments on summer forest microclimate in southeastern Missouri Ozarks

1.2.4 Microclimate measuring techniques

Chapter 7.5 (p. 231) in Foken (2008): Micrometeorology

a) Radiation

Chapter 6.2.1 (pp. 189-193) in Foken (2008): Micrometeorology

b) Wind

Chapter 6.2.2 (pp. 193-200) in Foken (2008): Micrometeorology

c) Temperature and humidity

Chapter 6.2.3 (pp. 200-208) in Foken (2008): Micrometeorology

d) Precipitation

Chapter 6.2.4 (pp. 208-209) in Foken (2008): Micrometeorology

1.2.5 Istruments, equipments

(sources of fictures: www.fernbank.edu, http://www.eol.ucar.edu/projects/ceop/dm/insitu/sites/baltex/lindenberg/forest/)

Figure 1 and 2: Forest tower

Figure 3. Anemometer and Wind Vane at 42 meters

Figure 4. Temperature & Relative Humidity (left), rain (center) Solar Radiation (right) at 42 meters

Figure 5. Anemometer and Wind Vane at 21 meters

Figure 6. Anemometer and Wind Vane at 10 meters

Figure 7. Under the CanopyTipping Bucket Rain Guage

Figure 8. Temperature & Rel Humidity Cover (center) Solar Radiation (left) at 21 meters

Figure 9-10. Throughfall and stemflow measurements

RELATED WEBSITES, PROJECTS AND VIDEOS

forest ecosystem services:

http://forest.jrc.ec.europa.eu/activities/forest-ecosystem-services/

http://www.youtube.com/watch?v=-FVlvWjJeTQ

International Network Measuring Terrestrial Carbon, Water and Energy Fluxes (FLUXNET):

http://www.ileaps.org/?q=node/66

forest microclimate research:

http://www.safeproject.net/projects/earth-atmosphere-linkages/microclimate/microclimate-stratification-in-modified-forests/

http://www.serc.si.edu/labs/forest_ecology/microclimate.aspx

http://www.wsl.ch/fe/walddynamik/projekte/BelCanClim/index_EN

http://www.youtube.com/watch?v=hqVi90B5UOg

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The resources in digital format:

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Foken_(2008)_Micrometeorology_Chapter_1.1-1.5.pdf

Foken_(2008)_Micrometeorology_Chapter_6.2.1-6.2.4.pdf

Foken_(2008)_Micrometeorology_Chapter_7.1-7.5.pdf

Parker_(1995)_Structure_and_microclimate_of_forest_canopies.pdf

Zheng_(2000)_Effects_of_sylvicultural_treatments.pdf

2 ROLE OF FOREST COVER IN THE HYDROLOGICAL CYCLE - CASE STUDY OF MEASUREMENTS AND MODELLING

2.1 Introduction

Land-atmosphere interactions related to the energy and water cycle are linked by the processes of evapotranspiration. Evapotranspiration is a collective term for all the processes, by which water in the liquid or solid phase at or near the earth's land surfaces becomes atmospheric water vapour (Dingman 2002). It is the sum of transpiration, interception, bare soil evaporation and evaporation from open water and snow.

Transpiration is the vaporization of water from the saturated interior surfaces of leaves to the surrounding air via microscopic pores called stomata (Hungate and Koch 2003). Stomata open and close in response to environmental factors such as light, temperature, CO_2 concentration and soil water. Interception is the part of the rainfall, which evaporates from the vegetation during and after the precipitation event. Bare soil evaporation is the vaporization of water directly from the mineral soil surface. It is only a small amount under forests because of the litter on the ground (Hewlett 1982).

Vegetation is basically influencing the water budget through interception and transpiration, which are affected by the leaf area and the rooting depth of the plants.

Leaf area index (LAI) is defined as a one sided green leaf area per unit ground area (Bonan 2008). It affects the radiative transfer process within the canopy and evapotranspiration from the plant surface. LAI varies temporally with age and phenology. Its value differs strongly among plant communities. Measurements by Járó (1959) showed the large variability of LAI (from 2.5 to 8.4) in different Hungarian forest types depending on age and site conditions.

Forests have larger leaf area compared to other vegetated surfaces. Larger LAI warms the surface due to lower albedo. But larger LAI also results in larger roughness length thus higher evapotranspiration rate in forests (Betts et al. 1997), which influences the exchange of both latent and sensible heat fluxes. The increase of the latent heat flux through transpiration is the major contributor to the cooling of the surface. The process is called evaporative cooling effect, which is the other basic biogeophysical feedback of forests on climate. It dominates primarily on the tropical regions leading to cooler and moister atmospheric boundary layer that may feed back to increased precipitation by affecting the larger-scale circulation (Brovkin 2002, Kleidon et al. 2007).

Vertical profile of leaf area in the forest canopy affects the distribution of radiation in the canopy. Larger leaf area increase the canopy shading, which leads to cooler air temperatures in the stem area, decrease of net radiation at the soil surface, therefore less bare soil evaporation in summer (Pitman 2003, Chang 2006).

Due to the higher evaporation rate, forests may increase the amount of precipitation. Chang (2006) summarizes the arguments and counterarguments to the possible precipitation-increasing role of forests. It is often assumed that forests enhance the precipitation formation increasing the effective height of mountains, which leads to an increase of the orographic precipitation. The higher transpiration rate of forests can lead to the increased vapour content of the air, which promotes the condensation and precipitation formation in the forested area. The basic counterargument is that the horizontal distribution of precipitation is mainly affected by the general circulation and topographic characteristics rather than by forests. For the precipitation formation water vapour content is not enough (Chang 2006).

The amount of precipitation, which reaches the ground surface infiltrates into the soil. Rooting depth and the soil texture determine the amount of water that can be stored in the soil, which is potentially available to the vegetation for transpiration (Kleidon and Heimann 1998). Available water holding capacity can be defined as the difference between field capacity (the amount of water after gravitational drainage) and wilting point (the amount of water in the soil when evapotranspiration ceases; Bonan 2004). Rooting depths have a large variability depending on plant species soil texture and soil water conditions.

Deep roots increase the water uptake and the amount of transpiration. It is an important characteristic in dry spells when moisture of advective origin diminishes. If there is enough moisture in the soil to continue evapotranspiration, local evapotranspiration can be an important contributor to precipitation.

2.2 Case study: Comparative Water Balance Study of Forest and Fallow Plots

2.2.1 Background

The relationship of vegetation cover and groundwater resources has drawn considerable scientific attention over the last decades. Many studies have shown that deforestation by logging or of natural origin (forest fire, wind damage) increased the average runoff from the affected area (e.g. Bosch & Hewlett 1982) and afforestation decreased runoff. Similar results were detected in recharge rates and groundwater depth, predominantly in dry regions. In Australia changes of vegetation from woodland to grassland or crops resulted in increases in recharge rates of one to two orders of magnitude (Maitre et al. 1999). The changes were largely due to the altered interception loss and the increased water extraction from the root zone. However, results of paired watershed research agreed only on the direction of the changes, not on their magnitude (Andressian 2004).

Comparative water balance studies of forest and low vegetation covers have generally shown higher water use of forest cover (Nachabe et al. 2005, Schilling 2007). Nachabe et al. (2005) analysed the groundwater consumption in a shallow water table environment and estimated the annual ET for a forested area (1320 mm) and for a pasture (700 mm) using detailed soil moisture and water table monitoring. At the same time, a few studies have found negligible differences in evapotranspiration of different vegetation covers (e.g. Roberts & Rosier 2005). The latter study found that, although there were seasonal differences, on an annual basis, the drainage below broadleaved woodland did not significantly differ from that below a pasture.

Due to climate change, air temperature is expected to rise significantly during this century (IPCC 2007). As a direct consequence of warmer temperatures, the hydrologic cycle will undergo changes with accompanying alteration in the rates of precipitation and evaporation. In Hungary, summer temperatures may increase by up to four degrees by the end of this century, while precipitation is likely to increase in winter and decrease in summer (Gálos et al. 2007).

The impact of climate change on groundwater resources was reviewed lately by Green et al. (2011). Although the uncertainty of predictions for change in groundwater recharge rates and discharge is large (e.g. future climate scenarios and groundwater extraction), numerous studies found that groundwater resources appear to be threatened by future climate change due to increased natural and human water demand.

In light of the water balance uncertainties and the increasing pressures on groundwater resources due to future climate change, a comparative water balance study of an oak forest and fallow vegetation plots was initiated in a drought-threatened lowland environment in Northeastern Hungary. Water balance components were estimated by the Hydrus 1-D numerical model (Simunek et al. 2005), calibrated on measured soil moisture and groundwater levels.

2.2.2 Materials and methods

Study area

The study plots are situated in the Northeast part of Hungary at latitude 47° 58′ N and longitude 21° 42′ E (Fig. 11), built up from sandy river deposits of the early Pleistocene (Borsy et al. 1981). The climte is continental; the mean annual precipitation (1951-

2000) is approximately 520 mm and mean monthly temperature (1951-2000) ranges between -2.4°C in January and 20.5°C in July.

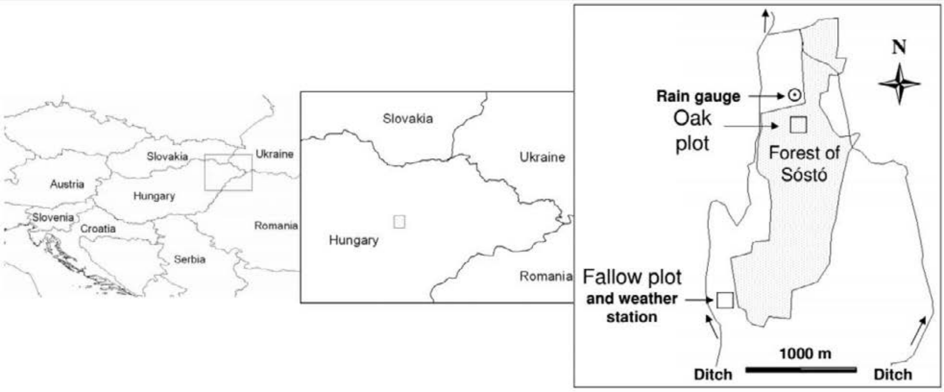

Figure 11. Location of the study area

The plots were located on the discharge area of the local phreatic groundwater flow system with shallow groundwater levels and groundwater supplies from the adjacent areas. Both study plots were selected so that the elevation of the plots above the nearby ditch was almost the same. The generally similar site conditions of the field plots made it possible to compare water balance components and groundwater consumption. The approximately 300 m distance from the nearby ditch minimized any effect that floods had on water table levels. Surface runoff was not observed since the slope of the plots was less than 2‰.

The naturally regenerated oak forest had 60% pedunculate oak (*Quercus robur*) which are 20-25 m high and the density is 270 trees ha^{-1}.The fallow plot, situated about 3 km from the oak plot, is part of an agricultural field that had been plowed in the past, but it has not been seeded and cultivated now for several years and is under natural succession. The vegetation consists of furrow-weed with species like *Solidago gigantea, Artemisia vulgaris, Amaranthus retroflexus* and *Ambrosia artemisiifolia*.

The vertical distribution of the root system was surveyed in situ by taking three replicate volumetric soil core samples at six depths (0-0.2 m, 0.2-0.4 m, 0.4-0.6 m, 0.6-0.8 m, 0.8-1.0 m and 1.0-1.2 m) for both study plots. After separating the fine roots (diameter < 2 mm) by sieving the soil samples, they were scanned and the total root extent of each sample was determined by grid-counting. Finally, the fine root fraction of each layer was related to the total root extent of the profile. Fine roots reduced approximately linearly with depth at the oak plot (estimated root depth: 1.5 m) and logarithmically at the fallow plot (estimated root depth: 0.8 m).

The soil analyses included the sieving and hydrometer analyses of particle size distribution of the soil samples, taken at 0.2 m intervals down to a depth of three meters. At both plots the soil texture was compacted fine stand (0.02–0.2 mm) close to the surface varying between 80-99%. The clay and silt fractions were high below one meter depth at both plots and reach 30-35% and 20-25%, respectively. Three repetition of undisturbed soil samples for water retention were analysed at depths of 0.1, 0.3, 0.5, 0.7, 0.9 and 1.2 m by cylinders of 100 cm^3.

The maximum of the Leaf Area Index LAI (m^2 m^{-2}) was estimated by collecting leaf litter on the ground. At the oak plot, newly defoliated leaves were collected carefully from five locations (1 m×1 m) during late autumn of 2007 and dried in an oven (105°C for 24 hours). Determination of LAI included the calculation of the ratio of weight to leaf area for a subset of leaves and then for the whole sample. The average LAI of the samples was 3.9 m^2 m^{-2}. The 16-day Enhanced Vegetation Index (EVI) product of MODIS (Moderate Resolution Imaging Spectroradiometer) was used to describe the seasonal change of LAI. The 250 m resolution EVI was converted to LAI using the relationship, proposed by Wang et al. (2005).

At the fallow plot, the maximum leaf area index was estimated by leaf collection from three locations (0.5 m×0.5 m). All the collected leaves were scanned and the leaf area was determined by grid counting. The mean LAI of the three samples was 1.1 m^2 m^{-2}. The same leaf area index was used throughout the vegetation period. During the dormant season, we assumed the LAI 0.5 m^2 m^{-2}, based on the biophysical parameter table of Steyaert & Knox (2008) (Fig. 12).

The albedo was derived from the 16-day estimates of the MODIS images. The missing values of albedo in winter were assumed as snow cover and were replaced by an albedo of 45% at the oak and 75% at the fallow plot (Kondratiev 1969).

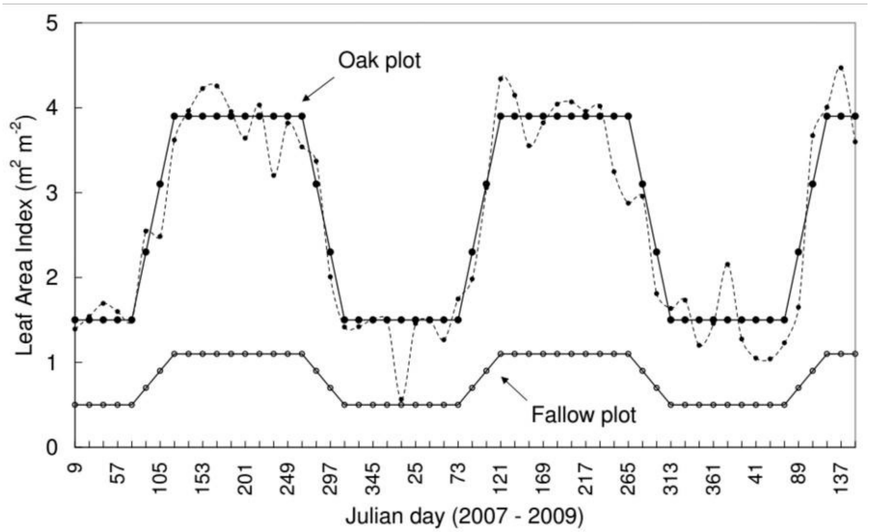

Figure 12. Seasonal change of LAI (Oak plot: dashed line - MODIS data, solid line - applied in the model, Fallow plot: solid line - applied in the model).

Monitoring at the plots

Meteorological variables, soil water content and groundwater level were monitored by automatic equipment.

A weather station (iMETOS, Pessl Instruments, Austria) at the fallow plot and an automatic rain-gauge (Rainlog Data Logger, Rainwise, USA) 500m from the oak plot was employed to monitor weather conditions. The volumetric water content was monitored with FDR (Frequency Domain Reflectometers) using Decagon EC-5 probes (Decagon Devices, Pullman, USA) with a time interval of 15 min. The probes were installed at depths of 0.1, 0.3, 0.5 and 0.7 m.Groundwater level was measured by a Dataqua DA-S-LRB 118 vented pressure transducer (Dataqua Elektronikai Kft., Balatonalmádi, Hungary) with time interval of 15 min. Manual groundwater level measurements were used to verify the reliability of the monitoring.

Water balance modelling with Hydrus 1-D

Model structure. The Hydrus 1-D (Simunek et al. 2005) model was applied for estimation of soil water content changes, actual transpiration and soil surface evaporation at both plots. Hydrus 1-D is a modelling software for analyses of water flow and solute transport in variably saturated porous media. The base of the model is the variable saturated vertical flow domain, where water flow is simulated (Fig. 13).

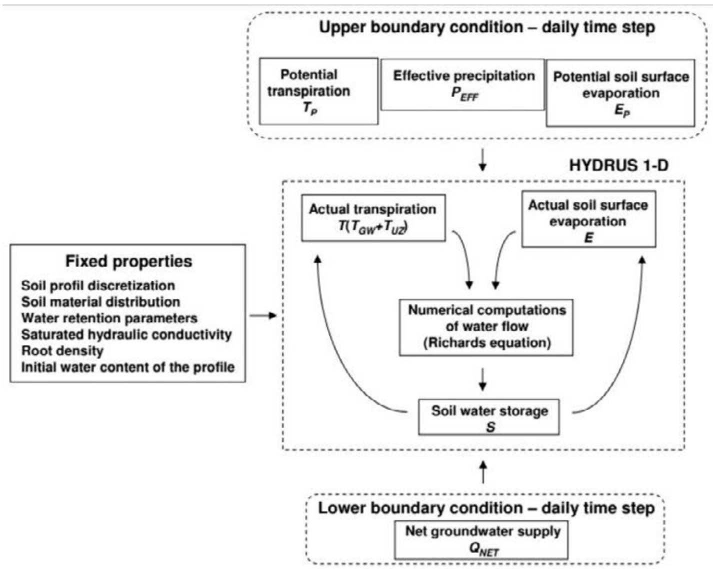

Figure 13. Structure of the model (P_{EFF}: effective precipitation, T_P: potential transpiration, T: actual transpiration, T_{GW}: groundwater consumption, T_{UZ} : transpiration from the unsaturated zone, E_P: potential soil surface evaporation, E: actual soil surface evaporation, Q_{NET}: net groundwater supply, S: soil water storage). All components are in mm day^{-1}.

The calculation of effective precipitation, canopy and litter interception loss, potential transpiration and soil surface evaporation, net groundwater supply, actual transpiration and soil surface evaporation is introduced by Móricz (2010) more in detail.

Model calibration. The observed soil water content and groundwater level data were employed to calibrate the Hydrus model at both plots. The model was calibrated specifically for this two year period and not used for future simulation (Móricz 2010).

2.2.3 Results

Comparison of observed and modelled results

The calibrated soil water contents compared well with observations at both plots (Fig. 14).

The discrepancies at the beginning of the growing season of 2007 in measured versus modelled soil water content may be attributed to the disturbance of the soil profile and vegetation at both plots during installation of the monitoring equipment. There were deviations at the fallow plot at a depth of 10 cm in December, 2008 and January, 2009 due to strong soil water freezing.

The calibrated groundwater levels compared quite well with measurements at both plots. Due to a malfunction of the pressure transducer, the continuous measurement failed at the fallow plot between November, 2007 and June, 2008. During this period regular manual groundwater depth measurements were employed to follow groundwater levels at the fallow plot.

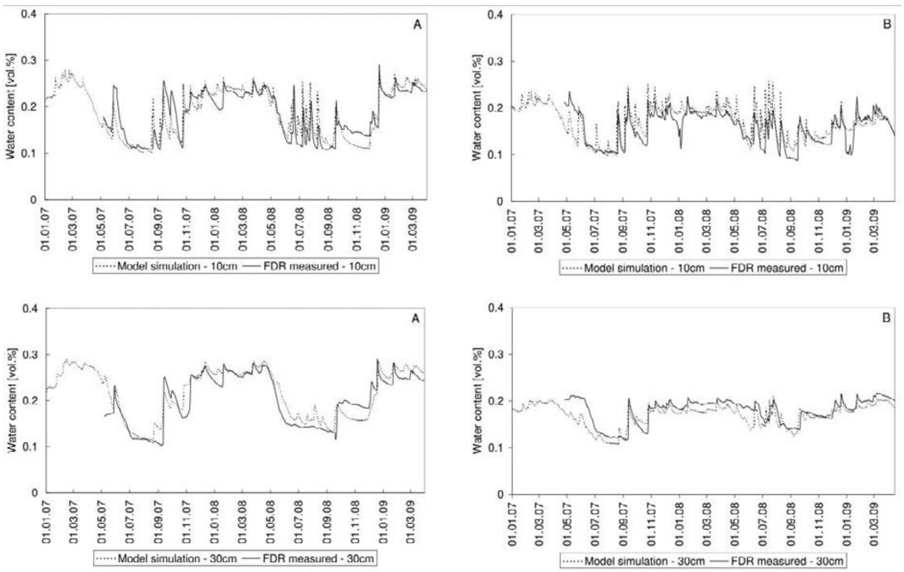

Fig. 14 - Comparison of measured and calibrated soil water contents at the oak (A) and fallow (B) plots

Water balance results

Total rainfall interception was twice as much in the forest than at the fallow plot considering the whole study period. In the 2007growing season, 38% of the rainfall was intercepted at the oak plot, while at the fallow plot it was only 15% of the gross rainfall. As a consequence of more rainfall in 2008, the ratio of interception loss to precipitation decreased slightly at both plots.

According to the Hydrus model, the oak forest transpired approximately 33% more than the fallow vegetation while groundwater consumption was three times higher during the study period.

Actual soil surface evaporation was only 4% of the total evapotranspiration at the oak plot and 26% at the fallow plot during the whole study period. The low evaporation amount of the oak plot was the consequence of the high surface resistance due to the litter layer and the shading effect of the canopy. Available net radiation at the soil surface, and soil surface evaporation rates were higher at the fallow plot; thus the soil surface dried out more rapidly than at the oak plot.

Since weather conditions were quite contrasting during the growing seasons of 2007 and 2008 we decided to compare the water balances for both plots from 1st of April until 30th of September.

Groundwater consumption T_{GW} was computed using the temporal changes of the capillary fringe in the Hydrus model results, which was 66% of the total transpiration at the oak plot while at the fallow plot it was only 38% in the growing season of 2007 (Fig. 15).

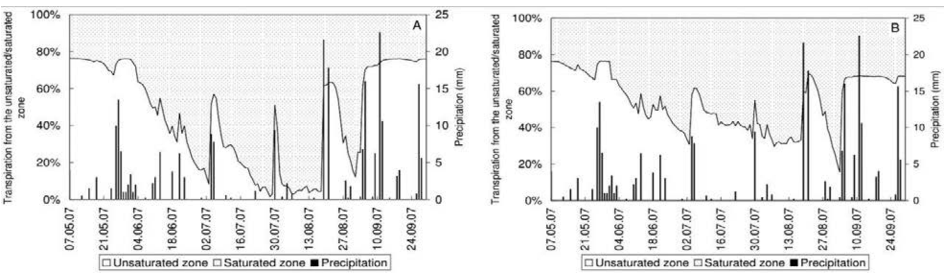

Figure 15. Proportion of the water uptake from the unsaturated and saturated zone and precipitation at the oak (A) and at the fallow (B) plots during the growing season of 2007

In this growing season, the water uptake showed the effect of drought in summer. Until the start of the summer, the transpiration from the unsaturated zone T_{UZ} was considerable from the total transpiration. The fraction of groundwater consumption increased to 60% at the fallow and to 90% at the oak plot in summer.

In the growing season of 2008, rainy weather provided a considerable amount of moisture for the unsaturated zone; thus the groundwater consumption was reduced from the preceding year. Groundwater consumption at the oak plot was 50% of the total transpiration while at the fallow plot it was 25% in the growing season of 2008 (Fig. 16).

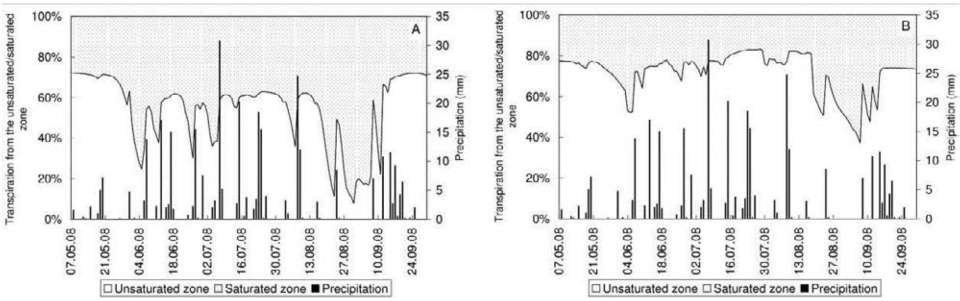

Figure 16. Proportion of the water uptake from the unsaturated and saturated zones and precipitation at the oak (A) and at the fallow (B) plots during the growing season of 2008

While in the growing season of 2007, both vegetation covers relied significantly on groundwater resources, in 2008 the evapotranspiration loss of groundwater was reduced considerably due to the rainy weather at both plots.

The water balance components of the growing seasons of 2007 and 2008 are shown in Tab. 1.

Table 1. Water balance components (mm) of the growing seasons of 2007 and 2008 at the oak and fallow plots

Water balance components	Growing season - 2007		Growing season - 2008	
	Oak plot	Fallow plot	Oak plot	Fallow plot
Precipitation (*P*)	261	261	383	401
Interception loss (*I*)	95	39	129	50

Soil surface evaporation (E)	22	139	41	154
Transpiration from unsaturated zone (T_{UZ})	208	235	255	260
Groundwater consumption (T_{GW})	405	144	255	87
Net groundwater supply (Q_{NET})	289	125	184	55
Change of soil water storage (S)	-180	-171	-112	-95

A meteorological tower was not set up at the oak plot, which contributed to the deviations of modelling results from the measurements. Air temperature and relative humidity at the fallow plot were applied above the canopy of the oak forest, which had an influence on the computation of potential transpiration and evaporation.

The empirical approach for computing Q_{NET} is further source of uncertainty since it is sensitive to the quality, the time-step of the record of groundwater levels and the readily available specific yield. The groundwater level data was carefully examined and suspicious measurements were not considered for further computation. The time-step for calculation of Q_{NET} was half an hour, considering the 15 min frequency of groundwater level readings, suggested by Gribovszki et al. (2008). The final value of the readily available specific yield was set to constant despite of its inherent variable nature in space and time.

2.3 Conclusions

Water balance components of an oak and fallow plot were estimated from 1 April, 2007 to 1 April, 2009 by calibrating the Hydrus 1-D model using soil moisture and groundwater level measurements. The study period included a dry (2007) and a wet growing season (2008).

For the entire study period, the Hydrus 1-D model results have shown that the total transpiration of the fallow plot was only two thirds that of the oak plot, while the soil surface evaporation in the oak plot was approximately one fifth of that in the fallow plot. The separation of transpiration into unsaturated transpiration and groundwater consumption has revealed that the groundwater consumption at the oak plot was almost three times higher than at the fallow plot. The groundwater consumption was close to 60% of the total transpiration at the oak forest and approximately 30% at the fallow plot.

By comparing the dry (2007) and wet (2008) growing seasons, we found that groundwater consumption was approximately 40% less in the wet than in the drier growing season, despite the fact that the groundwater level was deeper during the dry period. Thus, during the dry season both vegetation covers relied considerably on the available groundwater resources.

The results of the study have reinforced those previous studies that reported higher groundwater consumption of forests compared to other vegetation covers. Therefore, future afforestation in arid regions with shallow groundwater levels should pay attention to the large groundwater depleting effect of forest, especially in light of future climate change and human water extraction.

RELATED WEBSITES, PROJECTS AND VIDEOS

Forests and water (FAO): http://www.fao.org/docrep/010/a1598e/a1598e02.htm

Books: http://www.nap.edu/catalog.php?record_id=12223

http://www.springer.com/earth+sciences+and+geography/earth+system+sciences/book/978-94-007-1362-8

Forest hydrology research: http://www.forestry.gov.uk/fr/HCOU-4U4JAM

water cycle animation: http://www.youtube.com/watch?v=0_coZzZfC8c

land cover and hydrology of watersheds: http://www.youtube.com/watch?v=t632Bz8AQ0U

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http://www.youtube.com/watch?v=hU06Vir2Ipc

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3 CARBON CYCLE: THE ROLE OF FOREST VEGETATION

3.1 Introduction

Climate regulation through carbon sequestration is one of the ecosystem services of forests. They are the largest terrestrial C pool thus can have an important role in climate change mitigation. Exchanges of carbon between forests and the atmosphere are being influenced by human-caused and natural disturbances. In this way, land use changes - especially afforestation and deforestation - can have major impacts on carbon storage. Forest soils are also an important pool of carbon. They too are a vital part of the carbon cycle and can act as both sources and sinks. Forest ecosystems-climate feedbacks under future climate conditions are still large unknowns.

Organic matter production of forests strongly depends on soil, hydrological, and climatic circumstances, at the xeric forest limit primarily on the recurrent summer droughts. In the comparison of climate zones, the strong correlation between organic matter production and climate is obvious. The above-ground dendromass responds strongly to the worsening of climate, irrespective of tree species, while the below-ground parts remain unchanged. The carbon content of humus and soil increases toward drier climate.

3.2 Ecosystem services of forests

There are a number of components to the broad range of ecological services that forests provide. These include (Sousson et al.,1995):

- the regulation of water regimes by intercepting rainfall and regulating its flow through the hydrological system;
- pollution control;
- the maintenance of soil quality and the provision of organic materials through leaf and branch fall;
- the limiting of erosion and protection of soil from the direct impact of rainfall;
- regulating climate (e.g. C-sequestration); and
- being key components of biodiversity both in themselves and as a habitat for other species.

This chapter will focus on the carbon cycle and sequestration of the forest ecosystems.

3.3 Carbon cycle of forests

Forests play a key role in the carbon cycle. Through the process of photosynthesis they are able to absorb carbon dioxide from the atmosphere (figure 16). Trees partition the carbon that they capture into different products such as leaf, root, seed, wood and branch, these different fractions are referred to as biomass. Much of the carbon that is initially captured is emitted back into the atmosphere during respiration and decomposition. Only the carbon that is stored in woody biomass such as roots, stems and branch material is locked away for the longer term.

Exchanges of carbon between forests and the atmosphere are being influenced by human-caused and natural disturbances (e.g. forest fire, forest cutting). In case of deforestation, the stored carbon will be released to the atmosphere quickly or to the soil where it decomposes slowly and increases soil carbon content. In this way, land use changes - especially afforestation and deforestation - can have major impacts on carbon storage.

Forest soils are also an important pool of carbon. They too are a vital part of the carbon cycle and can act as both sources and sinks. At global scale the carbon that is contained in the worlds forests, if released would be enough to raise the carbon dioxide concentration in the atmosphere to over 1000 ppm and with it would follow a potentially catastrophic rise in temperature of 5-8°C. At a global scale maintaining the world's woodlands and forests is therefore an essential element of any measure to mitigate climate change.

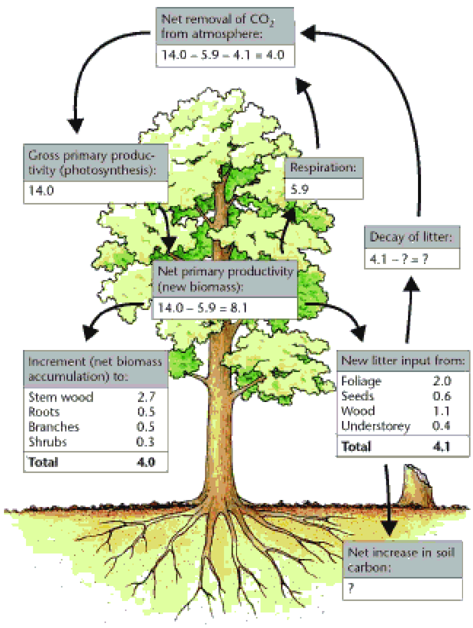

Figure 16. Carbon cycle of trees

Table 2 shows that average carbon levels sequestered in vegetation and soils differs among the major biomes. and among regions (figure 17).

Table 2. Average Carbon Stocks for Various Biomes (in tons per acre)

Biome	Plants	Soil	Total
Tropical forests	54	55	109
Temperate forests	25	43	68
Boreal forests	29	153	182
Tundra	3	57	60
Croplands	1	36	37
Tropical savannas	13	52	65
Temp. grasslands	3	105	108
Desert/semidesert	1	19	20
Wetlands	19	287	306
Weighted Average	***14***	***59***	***73***

Source: Adapted from Intergovernmental Panel on Climate Change, "Table 1: Global carbon stocks in vegetation and carbon pools down to a depth of 1 m [meter]," Summary for Policymakers: Land Use, Land-Use Change, and Forestry. A Special Report of the Intergovernmental Panel on Climate Change, at http://www.ipcc.ch/pub/srlulucf-e.pdf, p. 4.

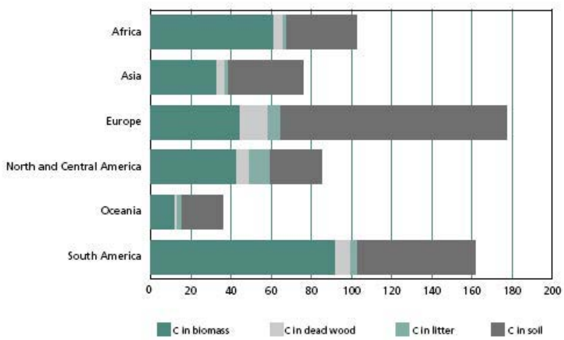

Figure 17. Total Carbon Stock (C) in forests by region 2005. Source: FAO: Global Forest Resources Assessment 2005, Progress towards sustainable forest management, Chapter 2: Extent of forest resources, p.35

The natural carbon sinks that can absorb and store carbon are ocean, forests, soil, peat and wetlands. In this way they can have an important role in climate change mitigation. Forest ecosystems are the largest terrestrial C pool of them. They store more than 80 % of all terrestrial aboveground C and more than 70 % of all soil organic C. Bonan et al. (2008) and Jackson et al. (2008) point out the differences of carbon sequestration between boreal, tropical and temperate forests that should be analyzed together with their biogeophysical feedbacks on the climate to assess the possible climatic benefits of these ecosystems.

Net-growing forests cause sequestration of C. After harvesting the life-cycle of the wood products is decisive. Therefore forest management and societal decisions both have significant influence on the carbon balance (Jandl et al. 2006). The first and most significant option to enhance C sequestration potential of forests lies in the establishment of new forests (through afforestation or reforestation). A second option is to foster the slow formation of a stabilized soil C pool. The C sequestration potential in forest soils is large, although smaller than that of agricultural soils (Jandl et al. 2006).

Forest carbon stocks could be potentially conserved and enhanced through a wide range of activities such as:

- Planting and/or regenerating trees on barren or non-forested land, in degraded forests, and in agricultural and urban landscapes. This includes concepts such as afforestation, reforestation, forestation, forest rehabilitation, forest restoration, agroforestry, urban forestry and enrichment planting.
- Conserving existing forests and avoiding their degradation or conversion to alternative land use. This includes concepts such as avoided deforestation, Reducing Emissions from Deforestation and Forest Degradation (REDD), and conservation of forest carbon stocks.
- Improved or sustainable forest management using options such as reduced impact logging (RIL), longer rotations, mixed ages and species.
- Managing harvested wood products.
- Soil (including peatland) conservation and rehabilitation.
- Use of forestry products for bioenergy to replace fossil fuel use.

- Tree species improvement to increase biomass productivity and carbon sequestration.

Through the introduced carbon related processes, ecosystems alter the biogeochemical cycles, thereby change the chemical composition of the atmosphere (Pitman, 2003), thus can lead to the increase or to the reduction of the projected climate change signal. Increasing atmospheric CO_2 content can lead to reduced terrestrial carbon uptake and greather accumulation of carbon in the atmosphere (Bonan 2008), which is a positive feedback that in turn can result in further global warming. However, the carbon – climate feedbacks under future climate conditions are large unknowns. Global warming will mobilize a certain, still unknown, quantity of soil C due to stimulation of he mineralization rate (Jandl et al. 2006, Booth et al. 2012). Higher CO_2 concentrations can also lead to the increase of the stomatal resistance thereby to the inhibition of the transpiration, which can amplify the global warming (Cao et al. 2010, Gopalakrishnan et al. 2011). Therefore for the quantification of the net climatic benefits of forests an integrated assessment of the processes, as well as accurate field measurements and modelling studies would be essential.

3.4 Estimations of the carbon content of forests and forest soil at the xeric limit

3.4.1 Below- and aboveground carbon stock in the dendromass of native tree species in Hungary

Forestry, in practice, uses special climate categories represented by different tree species (i.e. beech, hornbeam-oak, sessile oak - Turkey oak, forest steppe: treeless). Beech climate can be characterized by most humid conditions, whereas forest steppe is the warmest and driest from the classes. These categories indicate different growing potential, therefore, any change in the area of climate categories accompanies with variation of organic matter production of the forest ecosystem (Führer et al., 2011a,b).

The ecological value of forest sites can be characterized by organic matter production, which is influenced by the climate in a greater rate, than it was thought before.

The organic matter production ability can be characterized in the easiest way by the accumulated timber volume in the growing stock in unit area. It was determined, that in unit area of climate categories used in practice, the organic matter accumulated in the growing stock are the highest in Beech climate (321 m3/ha). In Sessile oak or Turkey oak climate it is only 207 m3/ha, and in forest-steppe climate it is less than 149 m3/ha.

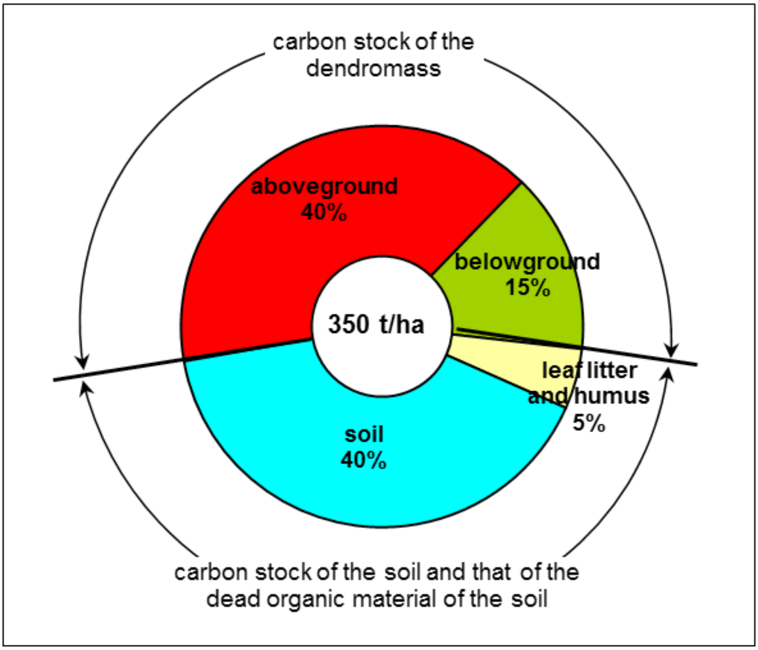

Figure 18. Carbon stock of the Turkey oak stand

Due to the climate change Turkey oak is becoming more and more important. The characteristic of Turkey oak is taproot system. When young it develops its roots deep into the soil very vigorously. Later lateral roots also become stronger and they will be able to develop farther from under the projection of the crown. In the experimental plot the volume of all roots in the upper 100 cm soil layer exceeds the 90% of the total root volume. This means that even if the soil conditions make possible the penetration of roots into deep layers, most of the root system encompasses and utilizes rather the one-meter tilth beneath the surface. Based on our measurements, the quantity of belowground dendromass (root swelling and root system) referring to carbon equivalent in the examined Turkey oak stand is 51 t/ha, of which 36 t/ha is in the root system. Its ratio out of the total dendromass (aboveground and belowground together) is 19 %. In a more unfavourable (drier) sample plot the value of 25% has been measured at a similar age Turkey oak stand. Consequently, the favourable climate conditions affect the organic matter production positively, the aboveground dendromass is higher, both in terms of ratio and absolute value. In a warming climate the amount of aboveground dendromass and the organic matter production will decrease (Führer et al. 2011).

3.4.2 Carbon sequestration of forest ecosystems and climate change

The ecophysiological observations and the investigation of the physiological processes of forests depending on weather have clearly proved that water supply in the main growth cycle (May to July) and in the critical months (July and August) essentially influences the growth and organic matter production of the forest (Führer et al. 2011). Relationship between meteorological parameters and girth-growth of trees (proportional with organic matter production) can be characterized by a simplified forestry aridity index (FAI) for Hungarian conditions (Führer et al. 2011a). By this index, the average weather conditions of different climate categories applied in forestry practise can be described. The smaller is the value of the FAI, the cooler and rainier is the climate (beech climate can be characterized by the lowest, whereas Turkey oak climate by the highest FAI values) FAI shows a causal relationship with the average yearly organic matter production (Führer 2007). The calculated FAI values show strong correlation with the carbon sequestration of the forest stand. Figure 4 shows that under present climate conditions, carbon sequestration is declining with increasing aridity among the forest climate classes.

The results may be utilised for forecasting productivity changes according to various scenarios. Based on the results of regional climate model simulations for the country, summers are projected to be warmer and drier (Gálos et al. 2007). These can result in a drastic shift in the forest climate categories and a species composition change on long-term time basis (Führer et al. 2013). The beech climate is projected to almost disappear from Hungary, the first of all on the xeric limit of its distribution, and Turkey oak as well as forest steppe climate is expected to expand. Based on figure 4, it would lead to less carbon sequestration in the forest dendromass and a decrease in production capacity of stands.

We expect a significant area decrease in good forest yield classes together with an increase in poor categories. The decrease in yield is caused by decrease of lumbered wood volume and more valuable wood assortments, as well. In case of the projected climate scenario, the highest decay in production capacity will be expected for Turkey oak (12 percent), while the lowest for beech (7.5 percent). (Führer et al. 2013).

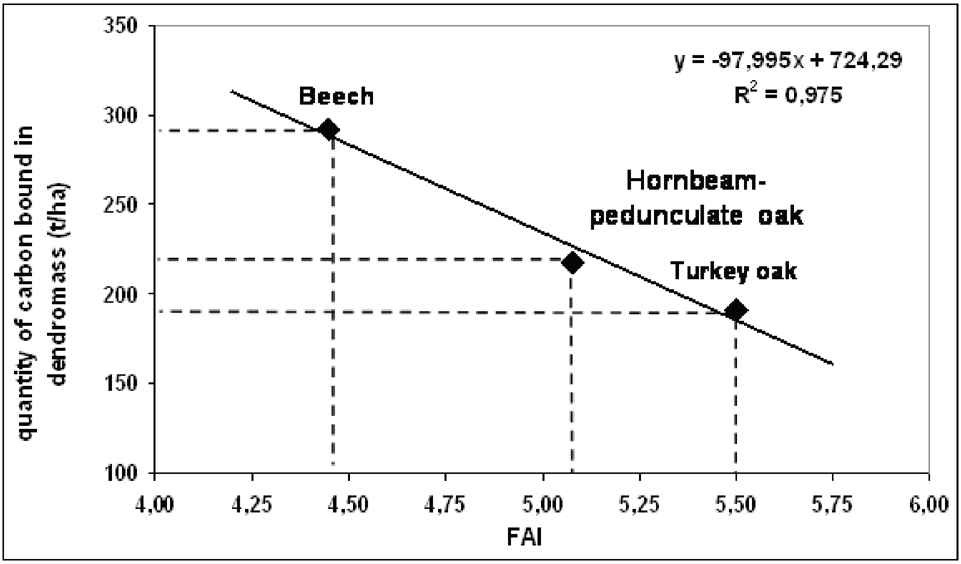

Figure 19. Correlation between aridity index (FAI) and the carbon stock stored in the dendromass of examined zonal forest types on optimal sites (Führer et al. 2011b)

The forecasted warmer and drier climate in growing season would also result in evident growth-loss of forest trees in Hungary. The growth-loss can be indicated by the decrease in wood volume of an area unit. Considering that cost of logging are determined mainly by the actual marketing circumstances independently on climate change; final consequence of the loss in production will be the decrease of revenues and profitability of forestry practice (Führer et al., 2013).

3.4.3 Soil carbon content and its estimated change under future climate conditions

Carbon content of forest soil and litter has been investigated in 35 deciduous forest plots in Southwest Hungary. Soil samples were collected from 0-5, 5-10, 10-20 és 20-30 cm depth, applying standardizted methods. Weight, pH value, carbon and nitrogen content as well as the mechanic composition of the samples have been determined.

The volumetric weights of the certain soil layers were also estimated for calculating the carbon content.

Carbon content of the litter samples has been determined separately for leaves, needles, twigs and decomposed.

Litter contains 5 tons carbon/hectar and the upper soil layer 46 tons carbon/hectar, which is almost 10 times as much as in the litter (figure 20). The estimated variability within the layer is larger than the carbon contend difference between the layers.

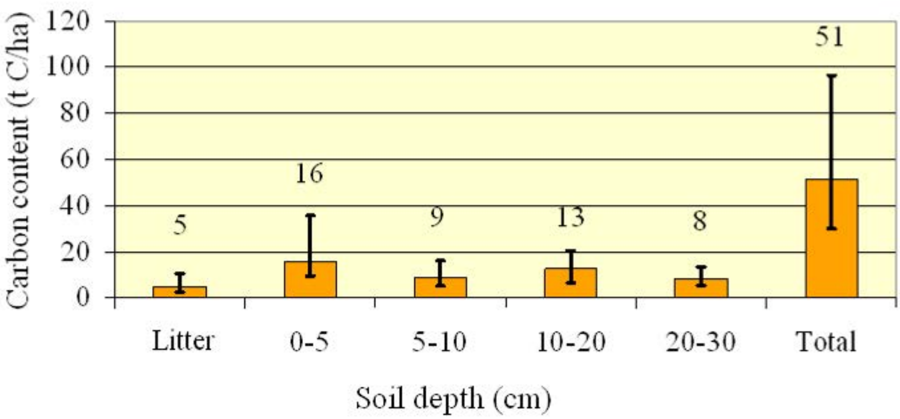

Figure 20. Carbon content of litter and forest soil

The drier and warmer climate can result in a decrease of the productivity of forests on the xeric (lower) limit of their distribution, where water availability is an important limiting factor. But it does not lead to the decrease of the carbon reserves of soil. The investigations and estimations showed that carbon reserves of soil may be higher under drier and extreme climate conditions. The reason for it is that the organic material and humus decomposition is prevented by drier climatic conditions in summer. 40-60 % of carbon stock of forest ecosystem can be found in underground organic matter in the Hungarian forests lands. The proportion of soil is 25-40% in total stock of carbon. It amounts to 27% carbon stored in dead organic material in the beech-wood forest, and 40% in Turkey oak forest. However, the total carbon of stock of Turkey oak forest ecosystem was smaller, carbon of stock in soil was larger than in soil of beech-wood forest (Bidló et al. 2011).

Expected unfavourable ecological effect of climate change can be a high risk for forest management.

RELATED WEBSITES, PROJECTS AND VIDEOS

carbon cycle: https://www.e-education.psu.edu/meteo469/node/160

https://www.fas.org/irp/imint/docs/rst/Sect16/Sect16_4.html

http://www.whrc.org/mapping/boreal/modeling.html

UN-REDD Programme: Reducing Emissions from Deforestation and forest Degradation:

http://www.un-redd.org/AboutREDD/tabid/102614/Default.aspx

http://www.thegef.org/gef/pubs/land-use-land-use-change-and-forestry-lulucf-activities

Forests and climate change (FAO) – carbon and GHGs: http://www.fao.org/docrep/005/ac836e/AC836E03.htm

Soil properties and processes that control soil carbon accumulation: http://www.youtube.com/watch?v=seJhFW6h_1U

Projects:

http://www.iww.uni-freiburg.de/researchareas/resource-and-carbon-storage

http://www.ucd.ie/carbifor/

http://www.forestry.gov.uk/fr/INFD-633DJ4

http://ucanr.edu/sites/forestry/Carbon/

Forest carbon dynamics; National Forest Sinks Committee Forest Carbon Risk Analysis Project

http://cfs.nrcan.gc.ca/projects/topic/36

Forest carbon sequestration:

http://www.youtube.com/watch?v=D-E-7RMbSZ0

http://www.youtube.com/watch?v=5xQnFhIRR88

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4 BIODIVERSITY GENERATION AND CONSERVATION SERVICES - ECOSYSTEM, SPECIES AND GENETIC DIVERSITY

4.1 Introduction

The analysis of quantitative data of common garden tests supports the concept that these tests offer unique possibilities for the realistic simulation of effects of climate change scenarios. Within the distributional range of a species, the response of a population depends on its adaptedness to its local environment. At the xeric limit, selection pressure narrows genetic variation and the increase in frequency of extreme events may result in growth decline and mortality. In the humid part of range, climate selection is less effective.

The asymmetry of response in different environments supports the hypothesis that the simultaneous action of plasticity and selection *maintains an adaptive non-equilibrium also at genetic level, similar to the one at ecosystem level.* In the distributional range of low moisture stress, warming will ease plasticity strain, which leads to growth acceleration instead of "decoupling" from adapted climate. The opposite growth trends in Western and boreal Europe, versus South-eastern-continental and Mediterranean Europe can be explained by the described phenomenon.

As expected rapid changes in the next decades will affect first of all the extant (already existing) forest stands, adaptation potential will mainly depend on the level of phenotypic plasticity. The importance of this trait should be recognized not only in breeding and improvement, but also in selection and use of forest reproductive material.

4.1.1 Xeric limits and genetics

Trees, as dominant components of forest ecosystems, are of high ecological importance in the temperate belt and receive much attention with regard to adaptation potential and future risks of diversity loss and extinction. Much of the climate change literature however is based on simulations and models, the genetic background of which are often deduced from results with annuals or other fast reproducing organisms. Genetic analyses of forest trees demonstrate that their genetic system and diversity parameters are *diametrically different* from annual plants or animals (Hamrick *et al*. 1992).

The crucial problem of realistic interpretation of adaptation to climate change is however the missing of field observations, such as common garden tests. In forestry, these tests have a very long tradition ("provenance tests"). Tests with trees are difficult to establish, laborious and time consuming to maintain and measure.

Another important field often missed when modelling and predicting responses to changes, is the production biology of forest trees (forest yield science). Large-scale assessments exist in forestry which analyse the response of forest stands to extant climate change effects and weather extremes (e.g. Briceno-Elizondo *et al*. 2006, Lapenis *et al*. 2005, Kramer and Mohren 2001). For instance, data show for large parts of Western Europe an unprecedented acceleration of forest growth in the recent warming decades, exceeding in some cases 50% (Spiecker *et al*. 1996). Interpreting these data might alleviate prediction difficulties of adaptive behaviour of tree populations. These shortcomings emphasise the importance of cross-disciplinary research (Mátyás 2006b).

4.1.2 Bioclimatic modelling of xeric limits needs genetic considerations

Climatic demands of tree species and of forest ecosystems have however attained a sudden actuality in the context of adaptation to predicted climatic changes. Bioclimatic modelling of distribution ranges is based on the concept that distributional patterns depend – among other factors – on the physiological tolerance limits to climatic effects. This generally recognised rule has to be extended by the statement that physiological tolerance is unquestionably determined by genetics. Tolerance can be defined as the ability of a genotype to maintain its fitness despite damage. It is also presumably genetically correlated with phenotypic plasticity, i.e. with growth vigour across environments (Weis *et al*. 2000; Mátyás and Nagy 2005). Limits of tolerance are therefore genetically set and will determine the presence or absence of species (Figure 21).

Thus, adaptive response to environmental stress is ultimately a genetic issue, and *correct bioclimatic modelling is strongly dependent on genetically set tolerance limitations.*

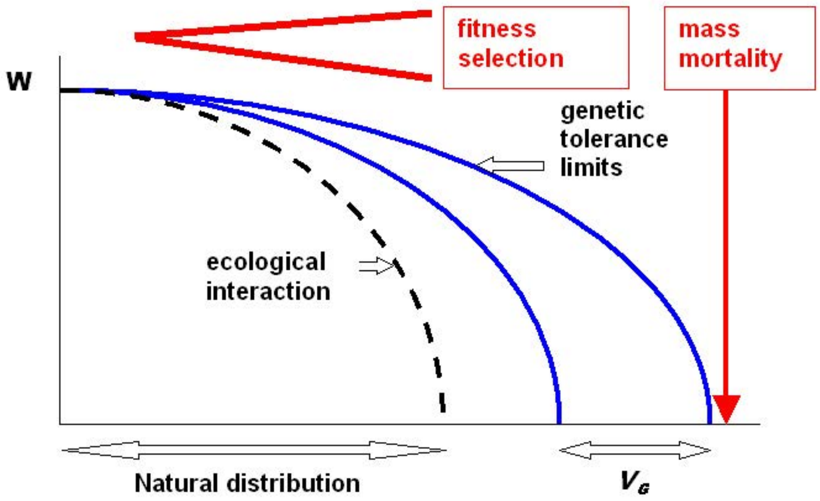

Figure 21. Ecological-genetic model of fitness decline and mortality triggered by worsening of climatic (site) conditions. The genotypic variance of limits of tolerance (V_G) represents the basis of natural selection. Due to competitive or trophic interactions in the ecosystem, the natural distribution is usually stronger limited, than the genetically set critical tolerance, as marked by the dashed curve (Mátyás 2006a)

4.1.3 Ecological and genetic options to adapt to changes at the xeric limits

Early symptoms of climate change effects at the xeric limits, such as loss of vitality, sporadic mortality, forest health problems indicate the constraints of adaptability. There are both genetic and non-genetic mechanisms operating on the individual, population, species and ecosystem levels, balancing changes in environmental conditions. On species and ecosystem or landscape level, a non-genetic possibility of responding to large-scale changes in the environment is *migration through seed dispersal*, including species substitution (succession, immigration) provided there are suitable species available.

Extensive studies on *long-distance gene flow through pollen* have shed light also on this very effective mechanism of constant replenishment of genetic resources, which most probably contributes to the unexpectedly high diversity and adaptability of tree populations (Hamrick *et al*. 1992). It is self-evident that migration and gene flow are functional across the whole range of distribution. Both mechanisms have however limited importance at the xeric limits, because they *rather support the escape of species and genes instead of the persistence* in marginal situations.

Genetically set adjustment mechanisms sustain persistence both on population and individual level. On the level of populations, *natural selection* adjusts the average fitness of a population to changing conditions. The directed genetic change of the population's gene pool towards an optimum state is genetic adaptation in the strict sense. It is a well accepted concept that the basic precondition for fast and effective genetic adaptation lies in sufficiently large variation, i.e. in sufficient genetic diversity (e.g. Booy et al. 2000, Beaulieu and Rainville 2004). Long-term genetic adaptability is therefore directly depending on the conservation or even reconstruction of broad adaptive genetic variance. The progress of selection will also depend on the intensity of selection pressure, as described by Fisher's theorem (Mátyás 2004). This progress may be counterbalanced by gene flow and migration.

Selection by climatic effects is certainly a key element among ecological factors. On the individual (genotype) level, *phenotypic plasticity* provides the ability to survive in a wide range of environments, without genetic change in the classic sense. Plasticity is the *environmentally sensitive production of alternative phenotypes by given genotypes* (DeWitt and Scheiner 2004). Plasticity implies that the phenotypic expression of genes is influenced by the environment, thus the organism may modify its responses within genetically set limits. It is especially effective in modular organisms such as trees, where the growth and developmental cycle may be strongly influenced by the environment. Phenotypic plasticity will set the limits of environmental heterogeneity within which a genotype or population can persist in its lifetime. In ecological literature, plasticity is often regarded as a non-genetic adaptation mechanism. It has to be emphasised that this trait is definitely heritable and also underlying climatic selection (Mátyás 2006a).

4.2 Estimation of aridity tolerance from common garden test results

4.2.1 Transfer analysis of common garden data

The principle of this approach is the use of ecological variables to express the change of environment through transfer to the test site. Adaptive responses to changes can be interpreted, generalized and compared more easily if expressed as ecological distances. To observe tolerance and plasticity, populations (provenances) are assessed in different environmental conditions. Regression analysis can be applied to describe the change in fitness. The slope of the function represents the sensitivity to changes and possible limits of tolerance. Taking growth and health condition as proxy for fitness, the function is interpreted as the species' reaction norm of fitness to the variable investigated (precipitation, drought). Thus, growth and survival of populations adapted to a given site, transferred and tested in other environments as part of common-garden tests, can be interpreted as a simulation of ambient changes at the original location. The transfer analysis validates the forecasting of adaptive response and of effects of environmental change (Mátyás and Nagy 2005; Rehfeldt *et al*. 2003).

4.2.2 Response to changes of climatic environment

Common garden tests of most tree species verify that populations originating from different climates show specific adaptation to local conditions and, accordingly, respond differently if grown under uniform conditions of a common garden.

The effect of temperature conditions on height growth of populations has been studied in six Scots pine tests situated in the centre of European Russia (Mátyás and Nagy 2005). The climate there is continental, summers may show moisture deficit. In order to exclude the effect of site quality, data were standardized by expressing height at age 16 in percents of locally adapted populations (relative height, see Figure 22). In the figure, transfer into cooler environments is shown by negative temperature sums. Tested populations were grouped according to their adaptedness into northern, central and southern groups.

The comparison of the regressions show that the three groups behave very similarly and display a marked depression in height growth with increasing aridity (i.e. higher mean temperature) of test location. This means that if introduced to more arid conditions than they were adapted to, populations react with growth decline expressed in relative height. On the other hand, the transfer into cooler (= more humid) environments resulted in growth acceleration compared to the local, autochthonous populations (Mátyás and Nagy 2005). Figure 2 illustrates that the simulation of climatic warming, i.e. the transfer into warmer environments, results in significant decline of productivity in the warmer part of the range, where moisture is in deficit in certain periods of the year.

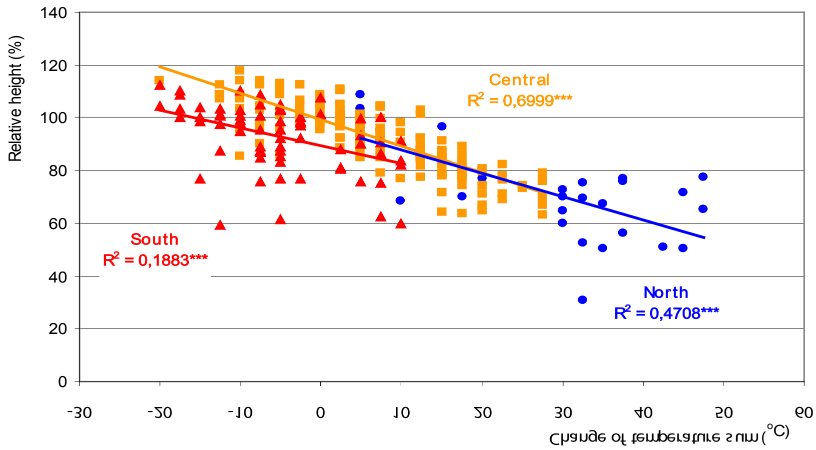

Figure 22. Linear regressions of relative tree height versus change of temperature sum (degree-days in °C) due to transfer by groups of provenances of Scots pine in 6 Russian tests (Mátyás and Nagy 2005)

4.3 Discussion

4.3.1 Adaptation maintains non-equilibrium state

It seems that the width of local adaptation is extended by phenotypic plasticity of genotypes towards less optimal environments. If environmental conditions improve (= transfer to milder sites), growth response will improve as well. Reaction norm of populations adapted to climates close to the xeric limit, exhibit an increased growth response northward of the original location. This effect is shown in figure 22.

It indicates that *populations under climatic selection pressure adapt to local conditions simultaneously by genetic (natural) selection and by utilizing phenotypic plasticity. With increasing distance from climatic conditions of the physiological/genetical optimum for a given species, populations toward the climatic limits of distribution display an increasing genetic adaptation lag, buffered by phenotypic plasticity.* As similar phenomena have been observed in numerous common garden experiments, on different species, cultivation or random effects such as gene flow are insufficient explanations. The migration hypothesis, i.e. that populations colonizing the site had no time yet to adapt locally, might hold at the thermal limits in the north, but not in the rest of the distribution area, and particularly not at the xeric limits. A parsimonious explanation is the assumption of *adaptive non-equilibrium* (Mátyás et al. 2008).

The proposed hypothesis of adaptive non-equilibrium means that within the distribution area of a (zonal) species, genetic adaptedness in the strict sense can be considered to be in an equilibrium state only in a narrow optimum zone. Approaching the thermal and xeric limits, the local populations get under increasing climatic stress due to the suboptimal functioning of genetic selection, which is buffered by phenotypic plasticity. Genetic diversity is then stabilised in a quasi-equilibrium state (Mátyás et al. 2008).

4.3.2 Conclusions for prediction and bioclimatic modelling of adaptive response

Asymmetry of response

An important outcome of transfer analyses is the asymmetry of response. The effect of environmental change on populations in different parts of the distribution range is divergent as different climatic factors exert their selection pressure.

The reaction of indigenous tree populations to warming will differ according to climatic zones. In the thermal-limited northern-boreal zone, the expected rise of temperature will lead to marked growth acceleration. At lower altitudes, in the temperate-maritime zone, growth will accelerate too, along with increasing or at least unchanged rainfall. In the sub-humid temperate-continental and sub-humid Mediterranean zones, however, even relatively minor temperature increases, coupled with growing drought stress, will trigger loss of compatibility, higher susceptibility to diseases, and increased mortality. At the xeric limits warming leads to relatively fast growth and productivity loss, and selective mortality (Berki and Rasztovits 2004; Mátyás 2005). It should be noted that the described phenomena are generalisations. Substantial deviations may be caused by the genetic system of the species, the evolutionary-migratory past and regional or local climate effects. For example, there are indications that in certain regions of the boreal zone, where moisture stress is already present due to low precipitation, higher temperatures and increased drought stress may also lead to incremental decline (Lapenis *et al*. 2005).

Changes in genetic diversity following climatic stress

Expectable genetic changes will be minor in the northern part of the distribution range despite the extreme speed of predicted (and already ongoing) changes. Improved growing conditions can be utilized through the plasticity potential of tree populations, without much migration or selection. As inherited plasticity will determine the response to changes, there is little room left for genetic adaptation. In temperate-Atlantic Europe, where moisture stress is predicted to stay low, populations will also be well buffered by their adaptability.

The situation is completely different along the xeric limit of main tree species, and at the limit of closed temperate forests. Here, natural selection becomes effective in the form of irregularly appearing health decline and mortality waves following weather extremes. High selection rates will certainly exert a strong effect on the genetic resources of exposed populations, and if stress situations aggravate, it may lead to local population extinction, even for once well distributed, dominant species (Mátyás et al. 2008). This underlines the importance of management and conservation of forest genetic resources (Ledig and Kitzmiller 1992, Mátyás 2000).

4.3.3 Conclusions for mitigation and management

At the xeric limits of distribution, migration or gene flow from better adapted populations is not happening. Regarding interannual fluctuations, with increasing mean temperatures, severity of extremes will increase too: aridity stress will therefore increase, which will cause additional stress at the xeric limits. Fast genetic adaptation is in contradiction with the accepted assumption of strong biological and ecological constraints. At the (zonal) xeric limits, an unlimited adaptation to declining environment is unthinkable, due to the evolutionary tradeoffs and constraints. This is proven by remarkable migrations and area shifts in the geological past (Mátyás et al. 2008).

Therefore the need of human intervention in mitigation has to be underlined (Mátyás 2006a). Due to ecological constraints to spontaneous adaptation, the policy of artificial translocation should be preferred instead of extensive enhancement of connectivity, at least with regard to tree species.

4.3.4 Consequences for forest management

The urgent necessity to put into practice the findings of quantitative genetics cannot be questioned. In addition some aspects of forest management should not be overlooked when predicting responses and formulating mitigation strategies. Most of Europe's forests have been and still are under strong human influence, and are managed according to periodic management plans. Especially close to the xeric limit, the proportion of nature-close forests is low, regeneration is mostly artificial. E.g. in Hungary, the rate of artificial regeneration is at present over 70 % on the Great Plain. The possibilities left for spontaneous processes, such as migration and succession are limited. Forest stand composition is primarily determined by forest policy and economic considerations. This means also that adjustments in species composition and in adaptive genetic potential may be achieved faster and more effectively compared to natural, spontaneous processes (Mátyás et al. 2008).

In drought stress climates, increment loss and higher incidence of diseases and pests will challenge the economics of forest operations, and will shift the emphasis towards the maintenance of ecological functions and conservation of stability and of genetic resources (Geburek and Turok 2005).

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Chapter 2.4

Climatic effects of land cover change

Áron Drüszler

ABSTRACT

Geological, paleontological and geomorphologic studies show that the Earth's climate has always been changing since it came into existence. The climate change itself is self-evident. Therefore the far more serious question is how much does mankind strengthen or weaken these changes beyond the natural fluctuation and changes of climate. Beyond the greenhouse effect and natural climate forcing processes (such as solar variability) there are also further anthropogenic influences with their various and partly non-negligible radiative effects. Land cover changes over time are one of the less successfully reconstructed anthropogenic influences on climate. It is well known that climate is the main factor of vegetation development through the precipitation, temperature, radiation and through the amount of carbon dioxide but the vegetation changes also affect the climate (partly as a feedback mechanism) via albedo, heat, water and momentum fluxes, as direct effects on the energy balance. There is also an indirect effect based on changes in the CO_2 concentration caused by the vegetation changes. This paper provides an overview of the scientific literature on climatic effects of land cover changes and through one detailed regional example (Hungary) also tries to show the mode of action of historical land cover changes on the regional climate system.

1 INTRODUCTION

Final aim of the climate research is to create correct forecasts for the future. For this reason we have to identify the individual processes which can influence our climate. Knowing the different climate forcing processes and evaluating the effects of their changes can help us to achieve this goal.

The atmospheric CO_2 concentration increase is well-known since the 18th century. This rise, together with the effect of other greenhouse gases, is equivalent to +2.5 Wm^{-2} increments of the planetary radiation balance and to ca. 1.5 °C of equilibrium global warming. However, up to the present only +0.74 °C temperature increase was globally observed (IPCC, 2007). This means that effects of other climate forcing processes and internal mechanisms may have the same order of magnitude.

Beyond the greenhouse effect and natural climate forcing processes (such as solar variability, changes is solar orbital parameters, volcanic activity), there are also further anthropogenic influences, i.e. the effects of sulfate aerosols, land cover change, stratospheric ozone depletion, black- and organic carbon aerosols and jet contrails, etc., with their various and partly non-negligible radiative effects. A comparison of these effects during the past 250 years is presented in the IPCC Report (*Forster* et al., 2007: Table 2.12 on p. 204.)

Land cover changes over time are one of the less successfully reconstructed anthropogenic influences on climate. The surface albedo, emissivity, evapotranspiration, soil heat flux and the aero-dynamic roughness of an area are affected by land cover changes. The surface roughness length affects the efficiency of the vertical exchange between the surface and the atmosphere in the planetary boundary layer. The surface albedo and emissivity modify the short wave and long wave radiation budget. Vegetation controls the partitioning of vertical turbulent heat fluxes between their sensible and latent forms (Bonan, 2004) through the plant-specific rate of evapotranspiration to the potential one. (The latter presumes unlimited availability of water from the soil). In addition, the vegetation's shading also influences the soil heat flux. These processes have a provable impact on the near-surface temperatures and atmospheric humidity (Drüszler et al., 2010, 2011).

This paper provides an overview of the scientific literature on climatic effects of land cover changes (Section 2.) and through one detailed regional example (Hungary) also tries to show the mode of action of historical land cover changes on the regional climate system (Section 3.).

2 LITERATURE REVIEW

It is well known that climate is the main factor of vegetation development through the precipitation, temperature, radiation and through the amount of carbon dioxide (Budyko, 1974; Prentice, 2001; Nemani et al., 2003), but the vegetation changes also affect the climate (partly as a feedback mechanism) via albedo, heat, water and momentum fluxes, as direct effects on the energy balance. There is also an indirect effect based on changes in the CO_2 concentration caused by the vegetation changes (Pielke et al., 1998; Bonan 2002).

If all forests of the Earth were in their natural potential conditions, then their total areas would cover 52-59 million km^2 (Ramankutty and Foley, 1998; Klein Goldewijk, 2001). However, mankind uses a substantial part of its continental surface for agriculture and other purposes, e.g. deforestation, urbanization, overgrazing, etc. According to Crutzen (2002), ca. 50 % of the natural surfaces of continental areas have already been changed by mankind. Though this process started as early as the stabilization of climate ca. 10,000 BP, about 75 % of all forest reduction took place after the Industrial revolution.

The existence of the vegetation feedbacks on climate are already proven by empirical and model studies, on monthly and seasonal averaging and at local, continental and global scales, as well. In a part of these investigations the ocean-atmosphere feedback methodology (*Frankignoul et al.*, 1998; *Frankignoul and Kestenare*, 2002) was adapted to the case of vegetation-atmosphere feedbacks, utilizing that dynamic memory of these feedbacks is also longer (1-2 months) than that of the atmosphere (1-2 weeks) (*Liu et al.*, 2006; *Notaro et al.*, 2006). In these studies the role of sea-surface temperature for the slow sub-system were played by the fotosynthetically active part of the solar radiation (FPAR), which value can be monitored from the satellites and characterizes the vitality of the vegetation.

According to these computations, the plant development depends mainly on temperature at the temperate latitudes, but it feeds back to the temperature, as well. This positive feedback may reach 10-25 % of the intra-monthly fluctuations. The feedback is the strongest in the cold-belt forests, e.g. in the Northern States of the USA and Canada, Northern Europe and Siberia. Here the feedback effect may be as strong as 1 °C

At the tropical and subtropical regions, however, the state of vegetation depends rather on precipitation. Though small feedback can be identified on precipitation in these regions, here the feedback does not reach 5 % of the total fluctuations. In some isolated areas, however, the amplifying feedback on precipitation may be higher than 10 mm/month. Such regions are e.g. North-East Brasilia, East-Africa, East-Asia and Northern part of Australia.

One of the most significant changes in land cover is the clearing of tropical forests in order to obtain new farmland, e.g. in the Amazon basin (Bonan, 2004). Though pastures of the tropical belt exhibit a higher albedo than the forests, it was still computed that some warming is the net result of the forest reduction (Gash et al., 1996, Gash and Nobre, 1997). The most likely cause of this warming is hidden in the root system of the trees, allowing much stronger transpiration in the dry and hot seasons (Kleidon and Heimann, 2000). The cooling effect of this mechanism, lost by deforestation is stronger than the warming effect of the albedo differences, as shown by model studies, (Bounoua et al., 2002).

The complete deforestation in Amazonia could already reduce the natural atmospheric precipitation, due to reduction of moisture sources for the atmospheric circulation (*Lean and Rowntree*, 1997). Partial clearing of tropical rainforests, however does not lead to precipitation reduction. Moreover, finer resolution models did even point at the possibility that existence of warmer spots within the forest cover may cause small-scale circulation, which could increase the convective activity (*Roy and Avissar*, 2002). Partial deforestation may even increase the precipitation of the Amazon region, itself, which is in coherence with the trends of precipitation observations (*Chagnon and Bras*, 2005).

Further model simulation targeted the effect of land cover changes on precipitation in the Estern part of the USA (Pielke et al., 1997). In the experiment, there were differences only in the land cover parameters; all atmospheric initial and boundary conditions remained unchanged. In the weather case they chose, the natural vegetation led to intense convective cloudiness (cumulus congestus), but without precipitation. The same atmospheric conditions with the present agricultural land cover led to intense precipitation and thunderstorm activity. In the given period of time, the observations supported the latter case with heavy precipitation (Shaw et al., 1997).

In arid and semi-arid regions of our planet, agricultural land cover, overgrazing and the use of trees for fuel modifies the energy-balance of the surface, the hydrological cycle and, hence, the climate (Bonan, 2004). Overgrazing increases the surface albedo (Charney, 1975; Charney et al., 1977), which, in turn decreases the temperature and vertical instability. Hence the less convective cloudiness led to decreased precipitation in these belts. Therefore, degradation of the landscape can even enhance permanent drought. The more recent studies also supported that large scale changes in the land cover of the Sahel-belt could lead to decreased precipitation in the North African regions (Xue and Shukla, 1993; Clark et al., 2001).

Spatial contrasts between the dry and the irrigated agricultural lands may lead to strong contrasts in the sensible and latent heat balance of the two surface types (Bonan, 2004). This can induce mesoscale circulation (Avissar and Pielke, 1989; Chen and Avissar, 1994). High evapotranspiration from the irrigated surfaces can cool the near surface layers of the atmosphere, which causes local circulation which is similar to the sea-land circulation. The same contrast may lead the same circulation in the boundary between the hot natural areas and cooler irrigated areas. The irrigation causes cooler climate conditions in Northeastern Colorado in the USA (Chase et al., 1999).

The effect of vegetation on climate can be seen in the transition zone between the tundra and taiga (Bonan, 2004). Differences in the albedo of taiga and tundra ecosystems, which are strongly driven by the presence or absence of snow, can be an important regulating factor even at the larger scales of atmospheric circulation. The taiga warms climate in contrast with the neighbouring tundra vegetation, as shown in several studies (e.g. Thomas and Rowntree, 1992; Beringer et al., 2005).

Calculations based on the land cover dataset of Ramankutty és Foley (1998) show that the strongest global effects took place in the last 300 years as farms replaced forests. In the previous 700 years (between ca. 1000 and 1700 AD) there was no significant effect of the land cover changes on the global mean temperature. In the last 300 years, mean global temperatures increased 0.09 °C and temperatures in the Northern Hemisphere increased 0.15 °C due to land cover changes (Shi et al., 2007). In the temperate and high latitudes this increase was as high as 0.3 °C with no significant changes in the tropical and polar regions.

Further studies supported the small decreasing effect of land cover changes on temperature, (Bertrand et al., 2002; Matthews et al., 2003), but these studies did not consider the indirect effect through increasing the CO_2 content of the atmosphere. This could, however, change the land cover induced temperature changes from cooling to warming!

Between 1850 and 2000, an estimated 156 Gt of Carbon was emitted into the atmosphere due to deforestation (Houghton, 2003). Brovkin et al. (2004) found that land cover was responsible for 15-35 % of the anthropogenic CO_2 emissions, depending on the details of the reconstructions, according to Ramankutty and Foley (1998), Klein Goldewijk (2001), or Houghton (2003). The ca. 35 % proportion was also supported by Matthews et al. (2004) applying a similar methodology, i.e. climate-vegetation-carbon-cycle modelling. This means, that land cover changes are among the causes of the CO_2-induced global warming.

As fossil fuel burning increased rather fast in the recent century, the relative contribution of the land cover to the atmospheric CO_2 uptake decreased (Betts, 2006). Between 1850 and 1900 this value fluctuated between 42% and 68%, but in the 1990's this contribution was only 5-35 %. According to Matthews et al. (2004), the common direct and indirect effect of land cover changes could cause an increase of ca. +0.15 °C globally between 1700-2000. The global radiative effect of land cover change on climate was also estimated by Hansen et al (1998) and further reports were also published by the recent two IPCC Reports (2001, 2007).

Mika et al. (2006) used preliminary radiative modelling to show that the effects of historical land cover changes in Hungary in the second half of the 20th Century were comparable to the primary effect of the increase of CO_2 concentration on the radiation balance of the surface-atmosphere system in the same time period. This relation in the local radiation balance, however, does not allow an analogous comparison with the climate consequences due to the main differences between the two climate forcing processes. Namely, the greenhouse gases were changing in rather similar way all over the world. Hence these effects have been distributed evenly in space, whereas the effects of land cover are different in the different regions.

For further detailed investigations the MM5 high resolution, non-hydrostatic mesoscale model was used to analyze the climatic effect of historical land cover changes during the 20th century (Drüszler et al., 2011). This work tries to answer the following questions: (i.) What kind of impact could the land cover changes have on the air temperature and dew point in Hungary? (ii.) How were these changes distributed in the country? (iii.) Could the land cover changes in Hungary affect the total precipitation in the last 100 years? (iv.) Could these differences of the land cover modify the individual precipitation events in the form of a possible "trigger effect"?

3 METHODS

3.1 Land Cover Data Arrays

The land cover changes were significant in Hungary during the 20th century according to the database of the Hungarian Central Statistical Office, and different historical maps. Two different land cover maps for Hungary were created in vector data format using GIS technology to restore the historical land cover changes. The land cover map for 1900 was reconstructed based on statistical data and two different historical maps: the derived map of the 3rd Military Mapping Survey of Austria-Hungary (*MMS*, 1910) and the Synoptic Forestry Map of the Kingdom of Hungary (*Bedő*, 1896). The land cover map for 2000 was derived from the CORINE land cover database (*CORINE*, 2000).

Significant land cover changes were found in Hungary during the 20th century according to the examinations of these maps and statistical databases.

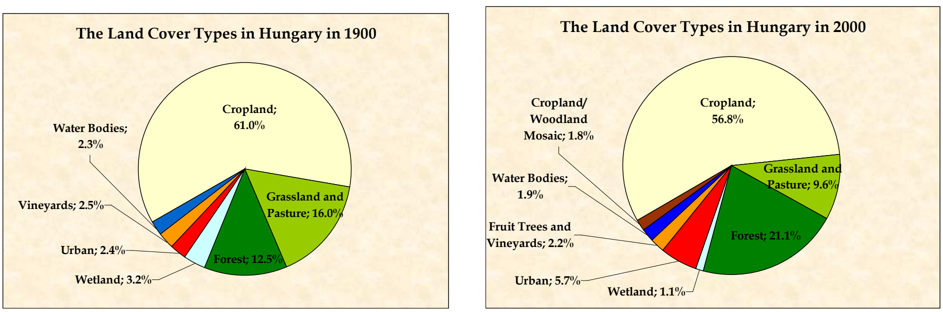

Figure 1. Fractional distribution of the land cover types in Hungary at the beginning (a) and at the end (b) of the 20th century

These maps show that the percentage of area of *cropland* in Hungary decreased from 61.0% to 56.8% between 1900 and 2000, while the urban areas increased from 2.43% to 5.69%. Significant changes also occurred in the percentage of *forests* and *grassland*. The forested area increased from 12.50% to 21.07%, while grassland decreased from 15.99% to 9.53% by 2000 (Fig.1).

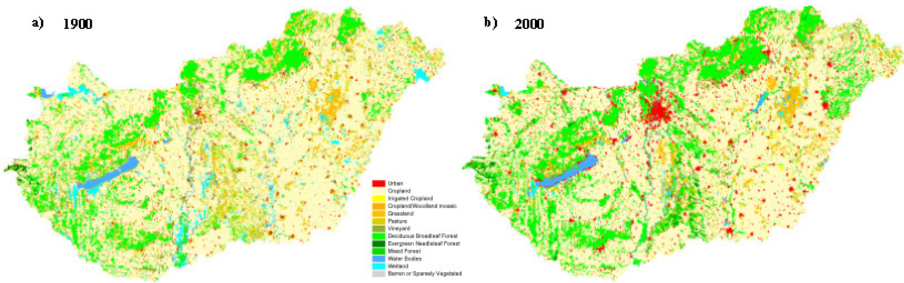

Figure 2. Land covers in Hungary at the beginning (a) and at the end (b) of the 20th century according to the MM5 land cover categories

3.2 MM5

The MM5 non-hydrostatic dynamic model (Grell et al., 1994) was used to further evaluate the meteorological effects of these changes. The MM5 is a numerical model, used worldwide, which is one of the main tools of the Hungarian nowcasting system too. The lower boundary conditions for this mesoscale model were generated for two selected time periods (for 1900 and 2000) based on the reconstructed maps (Fig.2). The horizontal resolution of the numerical model was 2.5 km in each case.

Table 1. The pre-defined macro synoptic situations for Hungary, their long term (1961-1990) mean frequency (during the time period from April to September) and the dates of the model runs

Pre-defined Macro-synoptic Situations for Hungary (Péczely, 1983).	Mean Frequency	Selected Dates
The weather in Hungary is determined by:		
((mCc)) the back of cyclone (possibly its cold front)	8.77%	**28h Aug, 2006,** 00 UTC + 48h **5th July, 2007,** 00 UTC + 48h
((AB)) the anticyclone over the British Isles (or North See)	7.97%	**13th July, 2006,** 00 UTC + 48h **9th April, 2007,** 00 UTC + 48h
((CMc)) the back of a Mediterranean cyclone (possibly its cold front)	3.40%	**10th April, 2006,** 00 UTC + 48h **9th Aug, 2007,** 00 UTC + 48h
((mCw)) the front side of cyclone (possibly its warm front)	8.90%	**18th June, 2006,** 00 UTC + 48h **21st Aug, 2007,** 00 UTC + 48h
((Ae)) the cyclone that is on the east from the country	9.12%	**5th July, 2006,** 00 UTC + 48h **29th Sept, 2007,** 00 UTC + 48h
((CMw)) the fore side of Mediterranean cyclone (possibly its warm front)	6.42%	**5th April, 2006,** 00 UTC + 48h **4th May, 2007,** 00 UTC + 48h
((zC)) the zonal stream of the cyclone that is north of the country	3.48%	**19th May, 2006,** 00 UTC + 48h **8th May, 2007,** 00 UTC + 48h
((Aw)) the anticyclone that is west of the country	17.75%	**21st Aug, 2006,** 00 UTC + 48h **29th June, 2007,** 00 UTC + 48h
((As)) the zonal stream of the anticyclone that is south of the country	3.55%	**2nd Sept, 2006,** 00 UTC + 48h **13th July, 2007,** 00 UTC + 48h
((An)) the anticyclone that is north of the country	12.62%	**29th June, 2006,** 00 UTC + 48h **4th June, 2007,** 00 UTC + 48h
((AF)) the anticyclone over Scandinavia	4.47%	**9th June, 2006,** 00 UTC + 48h **14th April, 2007,** 00 UTC + 48h
((A)) the anticyclone over Hungary	10.67%	**10th Sept, 2006,** 00 UTC + 48h **20th Sept, 2007,** 00 UTC + 48h
((C)) the cyclone over Hungary	2.90%	**30th May, 2006,** 00 UTC + 48h **11th Aug, 2007,** 00 UTC + 48h

3.3 Stratified Sampling

The dynamic model was run with the same detailed meteorological conditions of selected days from 2006 and 2007, but with modified lower boundary conditions. The macro-synoptic type had to remain unchanged for at least 48 hours. The dates of the model runs were selected evenly within the six months of the vegetation period, (April to September). The set of 2×13 selected initial conditions represents the whole set of the macro synoptic situations for Hungary (Péczely, 1983; Table 1). 52 (2×2×13) forecasts were made with 48 hours of integration. The effects of land cover changes under the different weather situations were further weighted by the long-term (1961-1990) mean frequency of the corresponding macro synoptic types, to estimate the climatic effect with these stratified averages. This process is called *stratified sampling*.

4 RESULTS

The short summary of results was taken nation-wide for three climate variables (temperature (2m), dew-point depression (2m), and precipitation). According to the comparisons, climatic effects of the land cover changes on the meteorological variables near the surface were not negligible during the 1900s. On average nation-wide, they caused +0.15 °C temperature increase and a 0.18 °C increase in the dew-point depression during the vegetation period. The temperature difference has three well-defined maxima in the night hours (Fig.3). This is a consequence of the urban heat island phenomenon whose effect is strongest at night. The changes are most profound in those parts of the country where urbanisation was highest. For example, within the current borders of Budapest, the land cover change caused an average 1.2 °C increase in daily temperature during the vegetation period.

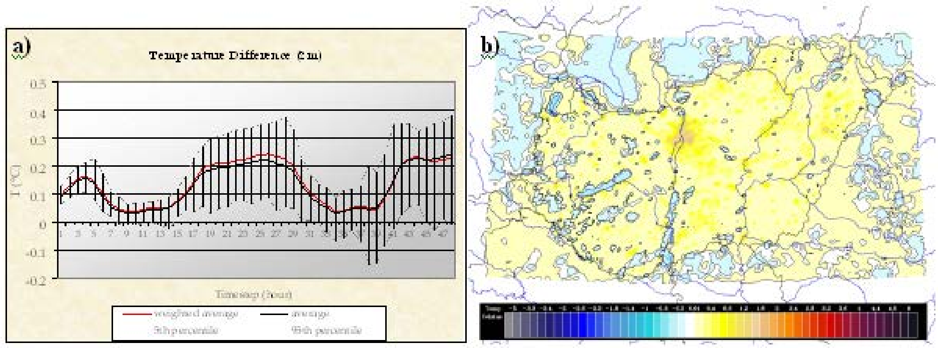

Figure 3. The temporal (a) and spatial (b) distribution of temperature changes due to the Hungarian land cover changes during the 20th century after applying the stratified sampling method. The 12th and 36th hours correspond to 2 p.m. local time.

Fig. 3b also shows that in a few places in the country, contrary trends were found from the national mean. Both the temperature and the dew-point changes (not shown) are the most expressed within the country's borders, because only the land cover changes within the country were available. Nevertheless, some effects of these changes within the country are also obvious outside the borders. Similar changes in the neighbouring countries, not involved into our simulations, could also affect the climate of Hungary.

Fig. 4 shows that according to the simulations, the two different lower boundary conditions did not cause significant changes in the total precipitation over Hungary. After applying stratified sampling, the simulated mean precipitation was around 6 mm during the 48 hour periods (5.95 mm with the land cover in 1900, 6.01 mm with the land cover in 2000). Nevertheless, by the analysing the spatial distribution of precipitation differences (Fig. 4b), we concluded that there are many regions where more than ±7mm precipitation anomalies were emerging in consequence of different land cover datasets. This means that the local uncertainty of precipitation forecast due to historical land cover changes exceeds the mean amount of the predicted total precipitation. Consequently we need an accurate description of current land cover in the modelling system to get correct precipitation forecasts.

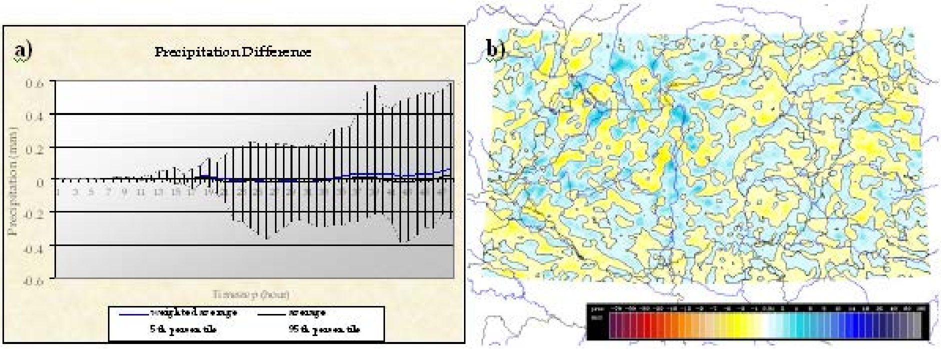

Figure 4. Effects of historical land cover changes on the area mean precipitation (a) and on the precipitation distribution (b) over Hungary after applying stratified sampling. The MM5 was integrated for 48 hours in all cases. The largest differences caused by the land cover changes exceed ± 7 mm/48 hours.

In certain cases the historical land cover changes could dramatically affect the local precipitation intensity and distribution. In particular cases this effect is connected with the phenomena that the emergence of a thunderstorm is also influenced by "minor" effects, such as temperature deviations over different land cover categories. We found that the simulated precipitation falls in a different regional distribution due to the varying lower boundary conditions, although the meteorological conditions were the same. We illustrate this phenomenon through analysing one selected weather situation.

In our selected case, (11^{th} August, 2007), during the running hours, there was a cyclone with its centre over Hungary. The simulated total precipitation was around 17 mm nation-wide. There were only small differences in this mean amount depending on which land cover was used during the simulations.

Applying the 1900 land cover, the forecasted total precipitation inside the borders was 17.8 mm; while using the 2000 land cover, it was 16.5 mm precipitation. Despite the small differences in these mean values (Fig.5a), the impact of land cover changes on local precipitation in some regions exceeds 40 mm during the simulated 2 day time period as shown in Fig.5b.

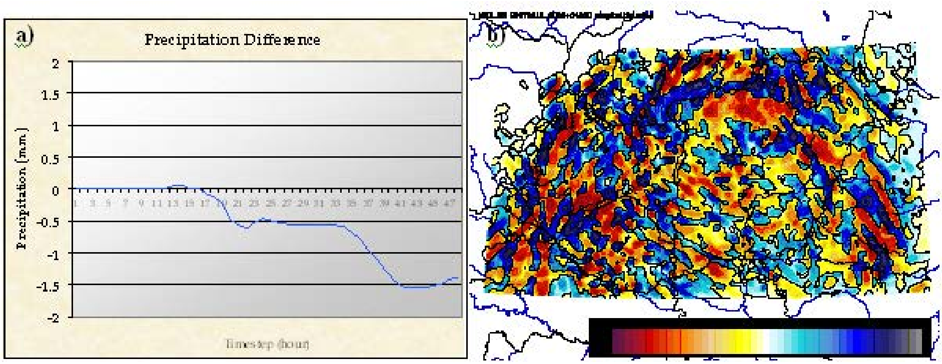

Figure 5. Effects of historical land cover changes on the area mean precipitation (a) and on the precipitation distribution (b) over Hungary as simulated for a (C) situation with a temperate latitude cyclone with its centre over Hungary, initialized at 00 UTC on 11th August, 2007. The MM5 was integrated for 48 hours, as in all other cases. The largest differences caused by the land cover changes exceed ± 40 mm/48 hours.

The odd thing about this situation is that the effect of the Tisza Reservoir on the precipitation intensity becomes visible between the 27^{th} and 29^{th} running hours (Fig.6). These selected hours clearly demonstrate how land cover changes can cause locally significant differences in predicted precipitation. By using a 1900 land cover only 1-2 mm precipitation was predicted for the region of the present reservoir (local time between 3 a.m. and 6 a.m.), because the reservoir did not yet exist at the beginning of the 20^{th} century. By using 2000 land cover, the large water body of the present reservoir functioned as a great source of heat and moisture for the air at night. Therefore, the model simulated heavy showers over the reservoir during the same 3 hour time interval.

These results clearly show that the large-scale weather conditions were unstable in this region at that time, but the essential heat for intensive convection producing local precipitation was available only in around the existing reservoir. Due to this fact, a heavy rainstorm appeared only in the simulation with present land cover datasets.

It should be noted that the meteorological effect of Tisza Reservoir varies between day and night. Contrary to the warming effect at night, water bodies usually cool the air near the surface in the day time.

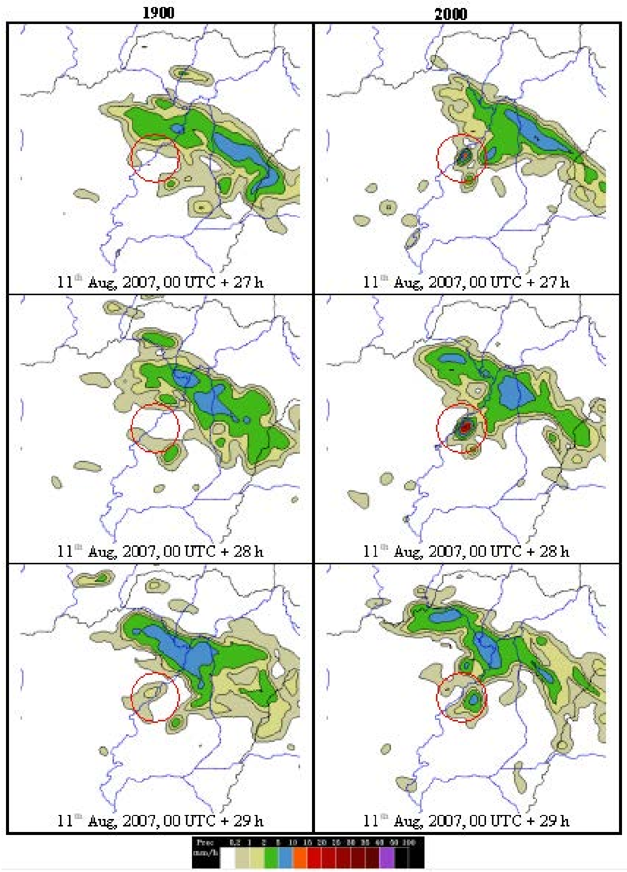

Figure 6. Effects of Tisza Reservoir on the local precipitation intensity as simulated for a (C) situation with a temperate latitude cyclone with its centre over Hungary initialized at 00 UTC on 11th August, 2007. The differences between the first and second column were caused by the different lower boundary conditions.

5 CONCLUDING REMARKS

After the analysis of MM5 dynamic model simulations, we found that the Hungarian land cover changes in the last 100 years caused an increase of +0.15 ° C daily temperature and +0.18 ° C dew-point depression during the vegetation period. This means that the near-surface air over Hungary is now warmer and drier than before due to the land cover change. It is also plausible, that the computed results show the maximum warming and drying over the urban areas. After the comparison of the warming effect of the land cover change with the documented warming in Hungary we concluded that the climatic effects of land cover changes are not negligible. Consequently, beyond other climate forcing processes, it is necessary to take land cover change into account by the interpretation of climate change in the past and for making scenarios for the future.

Since the climatic effects of Hungarian land cover change are based on 26 weather conditions only, the averaged results may be uncertain due to the relatively few samples of meteorological cases. Nevertheless we conclude that the increase of the daily temperature likely exceeds +0.1 °C, since all types exhibited warming between the 1900 vs. 2000 land cover types, and the increase was larger or equal to 0.1 °C in 19 of the 26 situations. The stratified sampling may not be as accurate as the true climatic average from long-term observations, but the order of magnitude in our estimations is probably correct.

It was also proven that the Hungarian land cover change does not have a significant impact on the average precipitation nation-wide. However, the impact on the regional distribution of precipitation is considerable, especially under unstable weather conditions. The present study clearly shows that MM5 precipitation forecast is very sensitive to the lower boundary conditions. (All other mesoscale models must also be sensitive). Since the Hungarian Nowcasting System uses the MM5 and WRF models, which work with the same land surface model, it would be reasonable to update the land cover database of these models by using current land cover maps. In addition, it is also necessary to update the land cover parameters of these models. The quality of the weather forecasting would be considerably improved.

6 RELATED WEBSITES, PROJECTS AND VIDEOS

Land use, land use change and forestry:

http://forest.jrc.ec.europa.eu/activities/lulucf/

IPCC special report on forests: http://www.ipcc.ch/ipccreports/sres/land_use/index.php?idp=0

http://unfccc.int/methods/lulucf/items/4122.php

http://ec.europa.eu/clima/policies/forests/lulucf/index_en.htm

http://en.wikipedia.org/wiki/Land_use,_land-use_change_and_forestry

Good Practice Guidance for Land Use, Land-Use Change and Forestry: HTTP://WWW.IPCC-NGGIP.IGES.OR.JP/PUBLIC/GPGLULUCF/GPGLULUCF.HTML

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Chapter 2.5

Afforestation as a tool for climate change mitigation

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ABSTRACT

This chapter introduce the results of regional-scale sensitivity studies carried out to investigate the role of afforestation in climate change mitigation for Europe. Applying the regional climate model REMO, the projected temperature and precipitation tendencies have been analyzed for summer, based on the results of the A2 IPCC-SRES emission scenario simulation. For the end of the 21st century it has been studied, whether the increased forest cover could reduce the effects of the enhanced greenhouse gas emission. The magnitude of the biogeophysical effects of afforestation on temperature and precipitation has been determined relative to the magnitude of the climate change signal. Based on the simulation results, afforestation may lead to cooler and moister conditions in most parts of the temperate zone thus can reduce the projected climate change. The largest relative effects of afforestation can be expected in northern Germany, Poland and Ukraine, which is 15-20 % of the climate change signal for temperature and more than 50 % for precipitation. The possible climate change mitigating effect of afforestation shows large differences among regions, which have been analyzed for Hungary more in detail. Results can help to identify the areas, where forest cover increase is the most favourable and should be supported to reduce the projected climate change. They can build important basis of the future adaptation strategies and forest policy.

1 INTRODUCTION

1.1 Regional climate projections for Europe

Several natural and anthropogenic processes influence the climate of the Earth. Human affect climate through increasing greenhouse gas concentrations, changing aerosol compositions as well as by land surface changes (IPCC, 2007). There are several recent EU-projects carried out in the last decade, to provide high-resolution climate change projections with focus on future climate changes and their impacts in Europe (Christensen et al., 2007; Jacob et al., 2008; van der Linden & Mitchell, 2009). These studies are based on the results of regional climate model simulations driven by different predefined greenhouse gas emission scenarios. The difference between the simulated climatic conditions for the future and for the present time period is the climate change signal. For the 21st century, projected climate change signals for temperature and precipitation show seasonal and spatial differences in Europe and also vary depending on the applied greenhouse gas emission scenario.

For the period 2021-2050 all regional climate models predict a quite robust surface warming in central and eastern Europe. The annual precipitation shows an increase in the northeastern and a decrease in the southwestern regions. (Christensen & Christensen, 2007; Kjellström et al., 2011). At the end of the 21st century, a warming is expected in all seasons over Europe, which is stronger than in the first half of the 21st century. All models agree that the largest warming for summer is projected to occur in the Mediterranean area, southern France and over the Iberian Peninsula. Less warming is projected over the Scandinavian regions. For winter the maximum warming occurs in eastern Europe (Christensen & Christensen, 2007). Results of the regional model simulations show a north-south gradient of annual precipitation changes over Europe, with positive changes in the north (especially in winter) and negative changes in the south (especially over the Mediterranean area in summer). For southern and central Europe the spatial distribution of the projected temperature and precipitation changes in summer refer to a marked shift towards a warmer and drier climate (e.g. Beniston, 2009).

1.2 Climatic effects of land use and land cover change

Temperature and precipitation play an important role in determining the distribution of the terrestrial ecosystems that in turn interact with the atmosphere through biogeophysical and biogeochemical processes. Vegetation affects the physical characteristics of the land surface, which control the surface energy fluxes and hydrological cycle (biogeophysical feedbacks; Pielke et al., 1998; Pitman, 2003). Through biogeochemical effects, ecosystems alter the biogeochemical cycles, thereby change the chemical composition of the atmosphere (Bonan, 2002; Pitman, 2003; Feddema et al., 2005). Forests have larger leaf areas and aerodynamic roughness lengths, lower albedo and deeper roots compared to other vegetated surfaces. They sequester carbon thereby alter the carbon storage of land.

Depending on the region, biogeophysical and biogeochemical feedbacks of land cover on climate can amplify or dampen each other (Arora & Montenegro, 2011). Through these land-atmosphere interactions changes of the land cover and land use due to natural and human influence alter climate and hence can lead to the enhancement or reduction of the projected climate change signals expected from increased atmospheric CO_2 concentration (Feddema et al., 2005; Bonan, 2008).

This section focuses on studies of the biogeophysical processes, which represent the contrasting climatic effects of forest cover changes on different regions, seasons and time scales. Changes of vegetation cover under future climate conditions enhance the warming trend in Scandinavian Mountains as well as the drying trend in southern Europe, but mitigate the projected increase of temperature in central Europe (Wramneby et al., 2010). Boreal forests have the greatest biogeophysical effect of all biomes on annual mean global temperature, which is larger than their effect on the carbon cycle (Bonan, 2008). If snow is present, the darker coniferous forest masks the snow cover. It is resulting in lower surface albedo compared to tundra vegetation or bare ground, which leads to higher winter and spring air temperatures (Bonan et al., 1992; Kleidon et al., 2007). Consequently, the change of vegetation from tundra to taiga under future climate conditions amplifies the global warming. Tropical forests maintain high rates of evapotranspiration. In this region, surface warming arising from the low albedo of forests is offset by the strong evaporative cooling that reduces global temperature increase (Bonan, 2008).

In temperate forests the albedo and evaporative forcings are moderate compared with boreal and tropical forests (Bonan, 2008; Jackson et al., 2008). Climate model studies for the temperate regions showed that replacing forests with agriculture or grasslands reduces the surface air temperatures (Bounoua et al., 2002; Oleson et al., 2004) and the number of summer hot days (Anav et al., 2010). Other studies show opposite results, where temperate forests cool the air compared to grasslands and croplands and contribute to higher precipitation rates in the growing season (Hogg et al., 2000; Sánchez et al., 2007, Gálos et al., 2011; 2012; 2013). In the Mediterranean region climatic effects of forest cover change can also vary during the summer months (Heck et al., 2001). In the period from April until mid-July potential vegetation cover conditions led to cooler and moister conditions due to the increase of evapotranspiration. In mid-July soil moisture dropped below the critical value and transpiration was almost completely inhibited. It resulted in dryer and warmer summer accelerating the projected climate change. Teuling et al. (2010) pointed out that the role of the forests in the surface energy and water budget is depending on the selected time scale: in the short term, forests contribute to the increase of temperature, but on longer time scales they can reduce the impact of extreme heat weaves.

These studies indicate that forests can enhance or dampen the climate change signal depending on various contrasting vegetation feedbacks, which can diminish or counteract each other. Furthermore the variability of the climatic, soil and vegetation characteristics as well as as well as the description of the land surface processes in the applied climate model also have an influence on the simulated vegetation-atmosphere interactions.

1.3 Research foci

The climatic feedbacks of land cover changes due to climate change and the regional land use politics as well as the role of the forests in the climate change mitigation on country scale are still unknown. In order to address this topic, our sensitivity study is focusing on the climatic effects of afforestation in Europe under future climate conditions based on the following research questions:

- In which regions does the increase of forest cover enhance/reduce the projected climate change?

- How big are the effects of forest cover change on the summer precipitation and temperature relative to the climate change signal?
- Which are the regions, where afforestation is the most beneficial from a climatic point of view?

On country scale, a more detailed case study has been carried out for Hungary. For the end of the 21st century, regional climate model simulations project a significant increase of summer temperature and a decrease of summer precipitation (Bartholy et al., 2007; Gálos et al., 2007). From ecological point of view Hungary (in the southeastern part of central Europe) has been selected as study region because here, many of the zonal tree species have their lower limit of distribution (Mátyás et al., 2009), which are especially sensitive and vulnerable to the increase of the frequency of climatic extremes, primarily to droughts. In these forests the more frequent and severe droughts at the end of the 20th century already resulted in growth decline, loss of vitality and the decrease of the macroclimatically suitable area of distribution (Berki et al., 2009). Under the projected climate conditions these species may disappear from this region (Berki et al., 2009; Mátyás et al., 2010; Czúcz et al., 2011). In the last 50 years, large scale afforestation was carried out in Hungary, which is planned to continue also in the near future. The influence of the historical land cover change on weather and climate has been investigated by Drüszler et al. (2011). For the future, forests can also have an important role in climate change mitigation. Therefore this case study is concentrating on the possible mitigation of the strong warming and drying of summers projected for the second half of the 21st century.

2 METHODS

Regional climate models have the potential to provide detailed information about the future climate on fine horizontal resolution. For studying the climatic feedbacks of land cover change in Europe regional scale analyses are essential because of the differences in the climate sensitivity among regions and the large spatial variability of the land surface properties and the related processes.

2.1 Experimental setup

In this study the REgional climate MOdel (REMO) has been applied for Europe, with horizontal resolution 0.22°. REMO (Jacob et al., 2007) is a regional three-dimensional numerical model of the atmosphere. Land surface processes in REMO are controlled by physical vegetation properties (like of leaf area index, fractional vegetation cover for the growing and dormancy season, background albedo, surface roughness length due to vegetation, forest ratio, plant-available soil water holding capacity and volumetric wilting point; Hagemann et al., 1999; Hagemann, 2002; Rechid & Jacob, 2006; Rechid et al., 2008a, 2008b). Land cover change in REMO can be implemented by modification of the characteristic land surface parameters.

Table 1. Analyzed data and time periods

Experiment	*Reference simulation*	*Potential afforestation simulation*
Characteristics	Present forest cover	Afforestation over all vegetated area [a]
Time period	1971-1990 2071-2090	2071-2090
Greenhouse gas forcing	IPCC-SRES emission scenario A2	
Horizontal resolution	0.22°	
Lateral boundaries	ECHAM5/MPI-OM[b]	

[a] based on Kindermann (pers. comm.)
[b] Roeckner et al., 2006; Jungclaus et al., 2006

The following experiments have been performed (table 1):

- *Reference simulation* for the past (1971-1990) with present (unchanged) forest cover.
- *Emission scenario simulation* for the future (2071-2090) with present (unchanged) forest cover applying the A2 IPCC-SRES emission scenario (Nakicenovic et al., 2000).
- *Potential afforestation* experiment for 2071-2090. The forest cover increase (figure 1) is based on the net primary production map for Europe derived from remotely sensed MODIS (Moderate-Resolution Imaging Spectroradiometer) products, precipitation and temperature conditions from the Wordclim database and soil conditions from the International Institute for Applied Systems Analysis (Kindermann, pers. comm.). The new afforested areas were assumed to be deciduous.

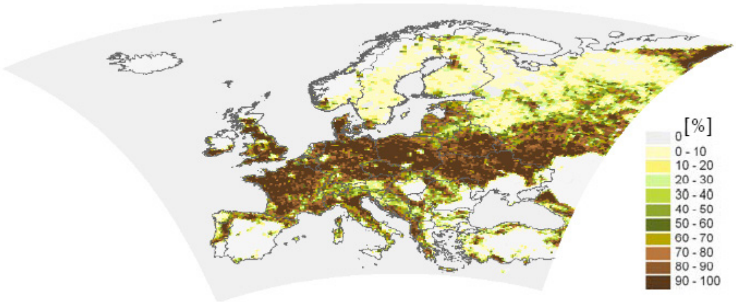

Figure 1. Increase of the forest cover in the potential afforestation simulation compared to the present (unchanged) forested area in the model (Gálos et al. 2012)

2.2 Main steps of the analyses

These analyses are focusing on the biogeophysical feedbacks of afforestation on the climate. Simulation results have been analyzed for May, June, July and August. In this study the mean of this period is considered '*summer*' (MJJA), because in these months water availability is especially important for the vegetation growth. The leaf area index of the deciduous forests reaches its maximum, which has a strong control on the land-atmosphere interactions.

- *Climate change due to changes in emissions has* been investigated analyzing the summer precipitation sums and 2m-temperature means for 2071-2090 (without any land cover changes) compared to 1971-1990.

- *Climate changes due to potential afforestation has* been calculated comparing the simulation results with- and without forest cover increase for the future time period (2071-2090).

- *Climate changes due to emission change and potential afforestation* have been determined comparing the results of the potential afforestation experiment (2071-2090) to the reference study in the past (1971-1990). The sign and the magnitude climatic effects of potential afforestation have been analyzed relative to the climate change signal.

For more detailed analyses, a case study has been prepared for Hungary over a smaller simulation domain, applying the same regional climate model and the same steps for data analyses. To get information about the maximum climatic effects of afforestation and its regional differences, the whole vegetated area of Hungary was assumed to be forest and the new afforested areas are all deciduous. The assumed maximal afforestation takes approximately 75 % increase of forest cover in country mean additionally to the existing 20 % forested area (figure 2).

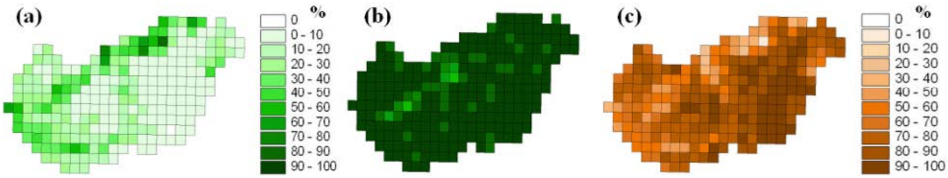

Figure 2. Forest cover in Hungary in the reference simulation (a) and in the maximal afforestation experiment (b). Increase of forest cover in the maximal afforestation experiment compared to the reference (c). Adapted from: Gálos et al., 2011

3 RESULTS

Simulation results of the sensitivity studies can be summarized as follows:

3.1 Climate change signal due to emission change (figure 3a):

- *Sign of the effects:* For the A2 emission scenario, a positive temperature signal is expected in whole Europe, which is projected to occur together with precipitation decrease in southern and central Europe and in the southern part of Scandinavia.
- *Magnitude of the effects:* The strongest warming and drying are projected for the Mediterranean area, southern France and over the Iberian Peninsula.

3.2 Climate change signal due to potential afforestation (figure 3b):

- *Sign of the effects:* In most parts of the temperate zone the cooling and moistening effect of afforestation dominates. Portugal, the Mediterranean coasts and the southern part of the boreal zone show a shift into the warmer and wetter direction. Warmer and dryer conditions over larger areas may occur in the boreal region.
- *Magnitude of the effects:* Afforestation has the largest climatic effects in the northern part of central and western Europe, where the temperature decrease due to afforestation may exceed 0.3 °C additionally to more than 10 % increase of the summer precipitation sum.

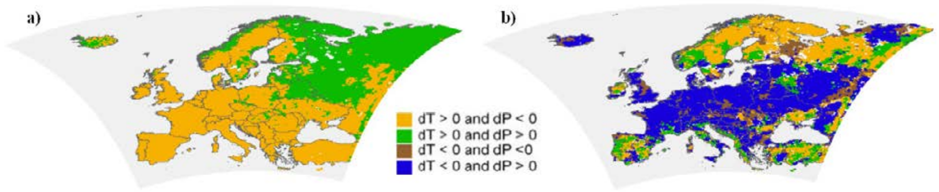

Figure 3. Climate change signal for temperature (dT) and precipitation (dP) due to emission change (a) and due to potential afforestation (b). Adapted from: Gálos et al., 2012

3.3 Climate change signal due to potential afforestation relative to the emission change (figure 4):

- *Sign of the effects:* In the largest part of the temperate zone precipitation and temperature anomalies due to forest cover increase show the opposite sign than due to emission change, which means that the climate change signal can be reduced by afforestation. Whereas in Sweden, in Spain and in some regions in the eastern part of the continent afforestation can amplify the climate change signal for both investigated variables.

- *Magnitude of the effects:* The largest climate change mitigating effects of afforestation can be expected in northern Germany, Poland and Ukraine, which is 15-20 % of the climate change signal for temperature and more than 50 % for precipitation. These changes are significant at the 90 % confidence level.

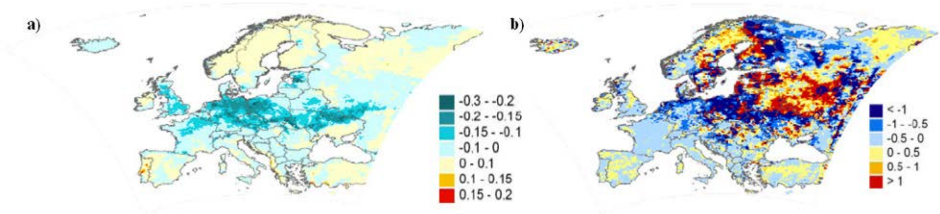

Figure 4. Climate change signal due to potential afforestation divided by the climate change signal due to emission change for temperature (a) and precipitation (b). The reddish colours are referring to the areas, where the changes of the analyzed climatic variables have the same sign for both afforestation and emission change. Whereas in the regions marked with bluish colours they show opposite sign. Adapted from: Gálos et al., 2012

3.4 Case study for Hungary (figure 5):

- *Sign of the effects:* The projected climate change signal for precipitation can be reduced assuming maximal afforestation.
- *Magnitude of the effects:* The strong warming and drying tendency projected for Southwest Hungary could be hardly compensated by forest cover increase. But in the northwestern region more than half of the projected climate change signal for precipitation can be relieved with enhanced forest cover.

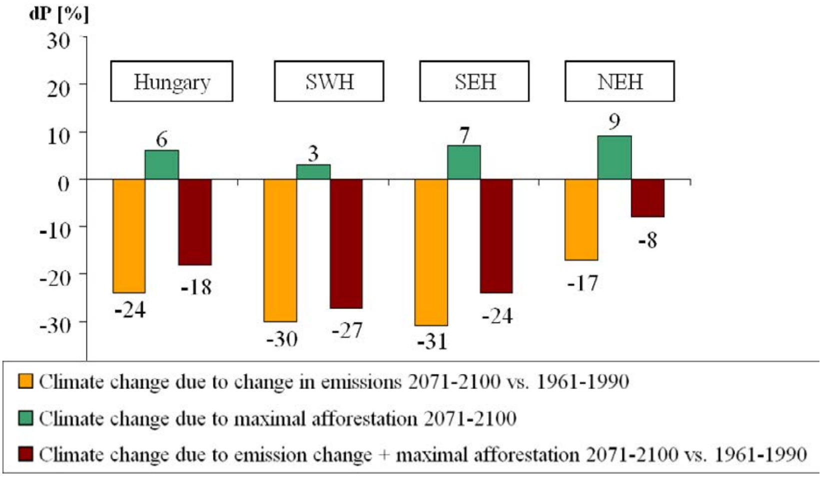

Figure 5. Change of the summer precipitation sum (dP) due to emission change (2071-2100 vs. 1961-1990), due to maximal afforestation (2071-2100) and due to emission change + maximal afforestation in Hungary and in the three investigated regions (SWH: southwestern part of Hungary, SEH: southeastern part of Hungary, NEH: northeastern part of Hungary). Adapted from: Gálos et al., 2011

3.5 Conclusions

A regional scale sensitivity study has been carried out to assess the possible climate change mitigating potential of forest cover increase for Europe, for the end of the 21st century. Based on the simulation results it can be concluded that only large, contiguous forest blocks have robust effect on the climate on regional scale. In the most climate change affected regions climatic effects of afforestation are relatively small, afforestation is not a substitute for reduced greenhouse gas emissions (Arora & Montenegro, 2011). But in other regions they can play an important role in reducing the probability and severity of climatic extremes (Gálos et al., 2011; 2012; 2013). On local scale the benefits and ecological services of forest cover are highly valued.

In our simulations, neither projected forest cover and forest composition shifts triggered by climate change, nor the vegetation dynamics were considered. One regional climate model has been applied driven by one emission scenario. The simulated impacts can also depend on the representation of the land surface properties and land cover related processes in the model (Boisier et al. 2012). Further challenge is the elimination of the model-depending effects and reduction of the related uncertainties. To achieve this, multimodel ensembles of climate model simulations and intercomparison studies are essential, which is the aim of recent EU-projects (e.g. LUCID; de Noblet-Ducoudre et al. 2012).

In these analyses we focused on the biogeophysical influences. But it is important to recognize that they can be intensified or dampened by the biogeochemical effects (e.g. carbon sequestration of forests and soil). Higher CO_2 concentrations can also lead to the increase of the stomatal resistance thereby to the inhibition of the transpiration, which can amplify the global warming (Cao et al. 2010; Gopalakrishnan et al. 2011). Therefore to draw appropriate conclusions for decision makers about the role of the forests in the climate change mitigation and adaptation, the combined effects should be analyzed.

Practical application of the results. From practical point of view, the investigation of the role of the land surface in the climate system gets even more important with the expected land cover change due to climate change and land use politics that differ among regions. Therefore regional scale information is substantial about the climatic feedbacks of the future land cover and land use for the adaptation to the climate change in agriculture, forestry and water management. Results of these sensitivity experiments help to identify the areas, where forest cover increase is climatically the most beneficial and should be supported to reduce the projected climate change. Here, the existing forests should be maintained. Thus the present study provides an important basis for the future adaptation strategies.

4 Related websites, projects and videos

Climate change, climate projections

CORDEX: http://www.meteo.unican.es/en/projects/CORDEX

ENSEMBLES: http://www.ensembles-eu.org/

PRUDENCE: http://prudence.dmi.dk/

IPCC AR5 2013 http://www.ipcc.ch/report/ar5/wg1/

Land use/cover change – climate research projects:

Land-Use and Climate, Identification of robust impacts (LUCID)

http://www.ileaps.org/?q=node/68

International Network Measuring Terrestrial Carbon, Water and Energy Fluxes (FLUXNET)

http://www.ileaps.org/?q=node/66

Climate Change – Terrestrial Adaptation & Mitigation in Europe (CC-TAME)

http://www.cctame.eu/

Operational Potential of Ecosystem Research Applications (OPERAS)

http://operas-project.eu/

IGBP - LUCC

http://www.igbp.net/researchprojects/pastprojects/landuseandcoverchange.4.1b8ae20 512db692f2a680009062.html

Climatic role of forests

http://www.youtube.com/watch?v=fwpfbDfKDMU

http://www.youtube.com/watch?v=isPGjChdby8

Climate change adaptation

http://www.youtube.com/watch?v=FO46sPwm4xk

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Chapter

3

Climate Change and Waste Land Restoration

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Climate Change and Waste Land Restoration

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1 INTRODUCTION TO CLIMATE CHANGE AND WASTE LAND RESTORATION

At a global scale, the waste management sector makes a relatively minor contribution to greenhouse gas (GHG) emissions, estimated at approximately 3-5% of total anthropogenic emissions in 2005. However, the waste sector is in a unique position to move from being a minor source of global emissions to becoming a major saver of emissions. Although minor levels of emissions are released through waste treatment and disposal, the prevention and recovery of wastes (i.e. as secondary materials or energy) avoids emissions in all other sectors of the economy. A holistic approach to waste management has positive consequences for GHG emissions from the energy, forestry, agriculture, mining, transport, and manufacturing sectors.

Waste generation does not result in positive impacts on climate. Waste treatment and disposal can have both positive and negative climate impacts. Therefore, an increasingly key focus of waste management activities is to reduce GHG emissions.

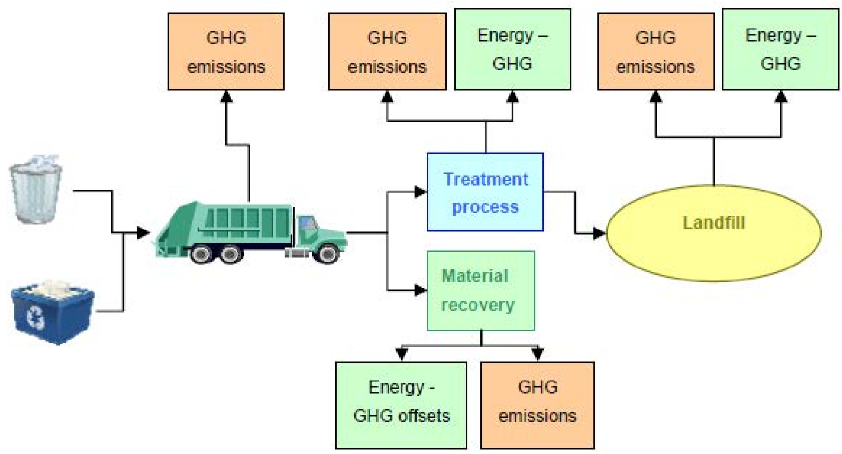


Figure 1. Simplified schematic of waste management system, and GHG emissions (applicable to urban waste management). Source: UNEP Waste and Climate Change Global Trends and Strategy Framework

2 WASTE MANAGEMENT AND GREEN HOUSE GASES (ghg)

2.1 Background

The waste management sector is in a unique position to move from being a comparatively minor source of global greenhouse gas (GHG) emissions to becoming a major contributor to reducing GHG emissions. Although minor levels of emissions are released through waste treatment and disposal, the prevention and recovery of wastes (i.e. as secondary materials or energy) avoids emissions in other sectors of the economy. A holistic approach to waste management has positive consequences for GHG emissions from the energy, agriculture, transport, and manufacturing sectors. A recent report by the US EPA estimates that 42% of total GHG emissions in the US are associated with the management of materials (US EPA 2009). A number of international organisations include waste and climate change initiatives in their portfolio of activities, recognising the considerable climate benefit that could be achieved through improved management of wastes.

2.2 Sources of GHG

2.2.1 Landfill

Methane emissions from landfill are generally considered to represent the major source of climate impact in the waste sector (this impact is quantified in later sections). It is worth noting that, if a broader view of waste management were taken, which included materials management, landfill methane would no longer be the largest source of GHG in the sector. The potential to save GHG through improved materials management (i.e. preventing material waste) is discussed in later sections.

Waste contains organic material, such as food, paper, wood, and garden trimmings. Once waste is deposited in a landfill, microbes begin to consume the carbon in organic material, which causes decomposition. Under the anaerobic conditions prevalent in landfills, the microbial communities contain methane-producing bacteria. As the microbes gradually decompose organic matter over time, methane (approximately 50%), carbon dioxide (approximately 50%), and other trace amounts of gaseous compounds (< 1%) are generated and form landfill gas. In controlled landfills, the process of burying waste and regularly covering deposits with a low permeability material creates an internal environment that favours methane-producing bacteria.

As with any ecological system, optimum conditions of temperature, moisture, and nutrient source (i.e. organic waste) result in greater biochemical activity and hence greater generation of landfill gas.

The gradual decay of the carbon stock in a landfill generates emissions even after Waste disposal has ceased. This is because the chemical and biochemical reactions take time to progress and only a small amount of the carbon contained in waste is emitted in the year this waste is disposed. Most is emitted gradually over a period of years.

Methane and carbon dioxide (CO_2) are greenhouse gases (GHG), whose presence in the atmosphere contribute to global warming and climate change. Methane is a particularly potent GHG, and is currently considered to have a global warming potential (GWP) 25 times that of CO_2 when a time horizon of 100 years is considered; the GWP is much higher (i.e. 72) when a 20-year time horizon is applied. See the table below:

Global warming potential (GWP) for a given time horizon (Forster et al 2007)

Greenhouse gas	GWP 20-yr (kg CO_2-e)	GWP (IPCC 2007) 100-yr (kg CO_2-e)	GWP 500-yr (kg CO_2-e)
Carbon dioxide CO_2	1	1	1
Methane CH_4	72	25	7.6
Nitrous oxide N_2O	289	298	153

Source: UNEP. Waste and Climate Change Global Trends and Strategy Framework.

Evidently, the choice of time horizon can have a dramatic effect on the estimated climate impact of methane emissions. Ideally, and in-line with IPCC guidance (1995), the choice of time horizon should reflect climate policy, or the climate effect of most concern. For example if the aim of a policy is to reduce the immediate or nearfuture levels of GHG, or minimise the rate of climate change, then a 20-year horizon is most appropriate. However, if the focus is on minimising the 'risk of long-term, quasi-irreversible climate or climate-related changes', then a 100 or 500 year time horizon is most suitable (Fuglestveldt et al 2001). However, as noted by an IPCC scientist: 'the time horizons tend to be misused or even abused. Industries tend to pick the horizon that puts their 'product' in the best light' (Fuglestveldt et al 2001).

In terms of reporting landfill emissions, the Intergovernmental Panel on Climate Change (IPCC) has set an international convention to not report CO_2 released due to the landfill decomposition or incineration of biogenic sources of carbon – biogenic carbon is accounted for under the 'land use / land use change and forestry' (LULUCF) sector (see discussion below, and refer to IPCC (2006) for accounting methodologies). Therefore, where landfill is concerned, only methane emissions are reported, expressed as tonnes of CO_2 equivalent (i.e. 1 tonne of methane is expressed as 25 tonnes of CO_2-e). In practice, methane emissions from landfill are rarely measured, but rather estimated for reporting (United Nations Environment Programme, 2010).

2.2.2 Aerobic composting

Aerobic composting processes directly emit varying levels of methane and nitrous oxide, depending on how the process is managed in practice. Closed systems, such as enclosed maturation bays or housed windrows, reduce emissions through use of air filters (often biofilters) to treat air exiting the facility.

Compost plants require varying, but usually small, amounts of energy input (with associated 'upstream' GHG emissions). Further GHG emissions occur 'downstream', depending on the application of the compost product – CO_2 will be gradually released as the compost further degrades and becomes integrated with soil-plant systems.

2.2.3 Anaerobic composting

Anaerobic digestion (AD) systems are enclosed in order to capture and contain the biogas generated by the digestion process. GHG emissions from AD facilities are generally limited to system leaks from gas engines used to generate power from biogas, fugitive emissions from system leaks and maintenance, and possible trace amounts of methane emitted during maturation of the solid organic output.

Such systems also consume energy, however plants are generally self-sustaining if appropriately operated (i.e. a portion of the biogas output generates energy for use in-plant). 'Downstream' GHG emissions will depend on the application of the matured digestate (as per aerobic compost product). (United Nations Environment Programme, 2010)

2.2.4 Mechanical biological treatment (MBT)

Mechanical biological treatment (MBT) encompasses mechanical sorting of the mixed residual waste fraction, with some recovery of recyclable materials (limited due to contamination), and separation of a fine, organic fraction for subsequent biological treatment.

The biological component may include anaerobic digestion with recovery of biogas for energy/heat generation, or aerobic composting to produce a biologically stable product for either land application (limited applicability) or use as refuse-derived fuel

(RDF) to substitute fuel in industrial furnaces (i.e. coincineration in cement kilns). MBT facilities vary considerably in terms of sophistication, configuration, scale, and outputs. GHG emissions associated with MBT are due to energy inputs (although AD systems may be self-sustaining), direct process emissions (this will depend on the air protection control system, such as a biofilter, attached to the aerobic composting component), gas engine emissions (for AD), and use of the composted organic output (disposed of to landfill or applied to land). There is some use of composted MBT output to remediate contaminated land, however most OECD countries strictly regulate the use of compost derived from mixed waste, and the majority is disposed of in landfill, or used as cover material for landfill operations.

2.3 GHG savings

In the context of the current report, the waste sector can save or reduce GHG emissions through several activities:

- Avoiding the use of primary materials for manufacturing through waste avoidance and material recovery (i.e. the GHG emissions associated with the use of primary materials – mostly energy-related – are avoided)
- Producing energy that substitutes or replaces energy derived from fossil fuels (i.e. the emissions arising from the use of waste as a source of energy are generally lower than those produced from fossil fuels).
- Storing carbon in landfills (i.e. carbon-rich materials that are largely recalcitrant in anaerobic landfill conditions, such as plastics and wood) and through application of compost to soils.

Indeed, depending on which GHG accounting convention is used, the waste sector is capable of generating a net GHG benefit through waste avoidance, material recovery, and energy recovery.

2.3.1 European Environment Agency (EEA)

Using a life-cycle perspective, this report analyses the greenhouse gas emissions from municipal solid waste management in the EU, plus Norway and Switzerland. Among other important conclusions, it finds that:

- improved municipal solid waste management in these countries has already cut annual net greenhouse gas (GHG) emissions by 48 million tonnes CO_2-equivalent between 1995 and 2008;
- the two main factors responsible for this improvement are reduced methane emissions from landfill and increased avoided emissions through recycling;
- if all countries fully meet the Landfill Directive's waste diversion targets, potential life-cycle GHG emissions from municipal waste management in 2020 could be cut by a further 62 million tonnes, which equals 1.23 % of their total GHG emissions in 2008;
- a complete ban on landfilling could cut emissions even further, reducing potential net emissions from waste management in 2020 by 78 million tonnes compared to 2008 — an amount slightly greater than Hungary's total emissions in 2008.

As this report makes clear, better management of municipal solid waste can reduce greenhouse gas emissions significantly. But to tap this potential, the EU's waste directives must be implemented fully — in particular the Landfill Directive.

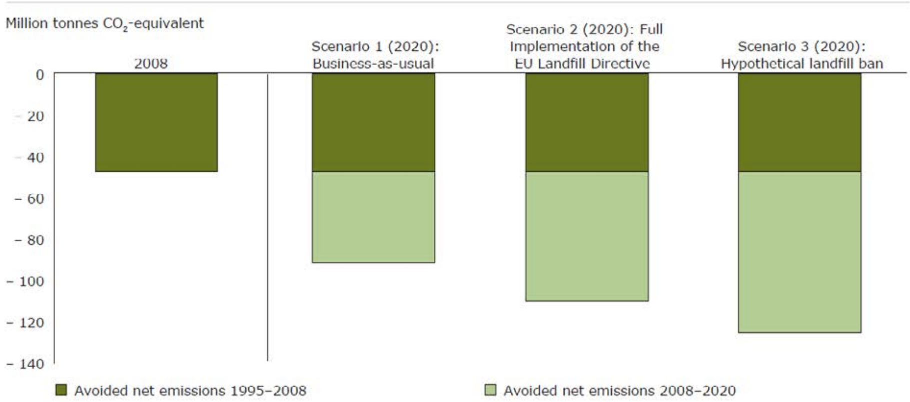
Beyond the progress so far, there is significant further potential to mitigate GHG emissions through better MSW management in the years to 2020.

In order to explore the potential effects on GHG emissions of new waste policies, the EEA and its ETC/SCP developed three scenarios on possible future paths for European MSW management:

- scenario 1 assumes business-as-usual (as presented in Figure 2.1);
- scenario 2 implies full implementation of the EU Landfill Directive;
- scenario 3 models a hypothetical landfill ban on all MSW by 2020 in all countries.

The next figure illustrates the net emission reduction achieved in the period 1995–2008 (in the first column) and the net GHG emission reductions in 2020 compared to 1995 for all three scenarios (in columns two, three and four). The net emission reduction is calculated as the difference between net emissions in 1995 and net emissions in 2008 or 2020, as appropriate.

Net emission reductions from MSW management in the EU (excluding Cyprus) plus Norway and Switzerland in 2008 and 2020 compared to 1995



Source: ETC/SCP. The European Topic Centre on Sustainable Consumption and Production.

2.3.2 European Commission

A resource-efficient Europe is one of seven flagship initiatives as part of the Europe 2020 strategy aiming to deliver smart, sustainable and inclusive growth 1. This is now Europe's main strategy for generating growth and jobs, backed by the European Parliament and the European Council. Member States and the EU institutions are working together to coordinate actions to deliver the necessary structural reforms.

This flagship initiative aims to create a framework for policies to support the shift towards a resource-efficient and low-carbon economy which will help us to:

- boost economic performance while reducing resource use;
- identify and create new opportunities for economic growth and greater innovation and boost the EU's competitiveness;
- ensure security of supply of essential resources;
- fight against climate change and limit the environmental impacts of resource use.

Increasing recycling rates will reduce the pressure on demand for primary raw materials, help to reuse valuable materials which would otherwise be wasted, and reduce energy consumption and greenhouse gas emissions from extraction and processing.

Improved waste management could cut significantly CO_2 emissions. For example, each year the EU disposes of 5.25 billion euro worth of recyclables such as paper, glass, plastics, aluminium and steel.

If this was recycled, the equivalent of 148 million tonnes of CO_2 emissions could be avoided annually. Improved management of municipal waste could result in 92 million tons of greenhouse gas emissions avoided in 2020 compared with 1995. At least 500 000 new jobs would be created in Europe if countries recycled 70% of their waste.

2.3.3 German Federal Ministry for the Environment

Following the entry into force of the Waste Management and Product Recycling Act in 1996, the practice of depositing untreated organic waste as landfill was gradually abandoned in the period up to June 2005.

Thanks to a marked increase in separate collection and processing, and also to waste avoidance and more efficient waste treatment and disposal methods, it has been possible to replace fossil fuels and raw materials. These improvements are entered as credits n the climate balance, where they lead to significant reductions in climate-relevant emissions and savings in fossil fuels.

The balance for 1990 was dominated by methane emissions from landfill sites. Since the balance for 2005 is drawn up without landfill, emission reductions and balance sheet results between 2005 and 2020 are no longer possible on the scale seen between 1990 and 2005. But a potential of over 5 million t CO_2 equivalent remains as an important contribution to the German climate protection target.

On the whole, the disposal paths of waste incineration plants and co-incineration display the greatest potential for reducing emissions of greenhouse gases. Waste paper recycling is also of great importance, while all other paths make smaller contributions to climate protection, and even the expenditure involved in the collection of waste is relatively insignificant, as it is shown in the table below:

Greenhouse gas emissions and remaining reduction options in the scenario period up to 2020, figures in million CO_2 equivalenmt

Disposal path	Emissions 1990	Emissions 2005	Emissions 2020-optimised	Reduction potential from 2005 to "2020-optimised"
Waste incineration	-1.00	-2.47	-5.42	-2.95
Co-incineration	-0.05	-2.16	-3.55	-1.39
Biowaste	0.10	0.19	-0.06	-0.25
Lightweight packaging	0	-0.54	-0.63	-0.09
Waste paper	-0.31	-1.71	-1.65	0.06
Waste glass	-0.39	-0.61	-0.61	0
Bulky waste/waste wood	-0.005	-0.27	-0.3	-0.03
Metals	-0.28	-0.78	-1.55	-0.77
Collection	0.48	0.36	0.36	0
MBT	0	0.21	0.19	-0.02
Landfill	39.23	0.09	0.02	-0.07

Emissions preceded by a minus sign mean that the CO_2 emissions for this disposal path (debit) are smaller than the credit for the processes replaced

Source: German Federal Ministry for the Environment.

2.4 Biogenic carbon

Many studies that examine the linkages between waste and climate change adopt the current IPCC convention for national GHG inventories of ignoring the contribution of CO_2 emitted from biogenic materials where these materials are grown on a sustainable basis. The argument is that during the growth of the plants, carbon has been taken-up and incorporated, and that same amount of carbon is emitted when burnt or aerobically decomposed – the carbon equation is effectively 'neutral'. There are several points to this argument that are worth considering:

- Climate change is time-critical – it is widely accepted that immediate reductions in global GHG emissions are essential to reduce the impact of climate change, immediate efforts should be made to minimise emissions of all CO_2, regardless of source.
- Plant growth – particularly of trees and longer-lived species – does not occur evenly over years and seasons, and the initial up-take of carbon by a seedling is far less than the uptake of carbon by a mature plant. Therefore it could be several

years before a flux of biogenic CO_2 emitted instantaneously from a process (i.e. combustion of biogenic carbon) is re-captured through plant growth.

- The majority of wood, paper, and agricultural materials that enter the waste stream have not been produced through sustainable forestry/land practices – unsustainable practices deplete the carbon stored in forests and soil over time. According to IPCC methodologies for reporting national GHG inventories, if any factor '...is causing long-term decline in the total carbon embodied in living biomass (e.g., forests), this net release of carbon should be evident in the calculation of CO_2 emissions described in the Agriculture, Forestry and Other Land Use (AFOLU) Volume of the 2006 Guidelines'. However, it is unclear how and whether this information is being recorded in all cases.
- In a national GHG inventory for IPCC purposes, where deforestation and re-growth is accounted for in the land-use category (LULUCF), there may be an argument for ignoring biogenic carbon. However, in an examination of the GHG impact of waste management systems, where solutions are being sought to reduce emissions in the waste sector, there is justification for including all sources of GHG.
- The benefits that accrue from a reduction in total CO_2, irrespective of the source, would seem to be the best indicator of the consequences of the different options. The key theme is climate change and how to mitigate it, not differentiation of carbon sources.

3 CLIMATE IMPACT OF WASTE

3.1 Potential GHG emissions reductions from materials management

Improved materials management practices throughout the material flow can have a significant impact on Green-House Gas (GHG) emissions. These materials management total technical potential scenarios include life cycle GHG emissions. These scenarios represent the estimated emission reductions that would occur if the scenarios presented were achieved, setting aside economic or practical limitations.

The total technical potential scenarios provided here are not representative of all possible approaches to reduce GHG emissions through materials management. Many of these scenarios focus on the waste stream because the data are limited on materials management strategies that focus on other points in the materials flow. As further research is completed, additional total technical potential scenarios will be developed to understand the GHG emission reductions that could be achieved throughout the materials flow. Potential reductions from some activities are summarized in the next boxes:

Summary of Total Technical Potential Scenarios

Source Reduction		Estimated GHG Emission Benefit*	
Reduce packaging use by:[63]	50%	40—105	MMTCO2E/yr
	25%	20—50	MMTCO2E/yr
Reduce use of non-packaging paper products by:[64]	50%	20—70	MMTCO2E/yr
	25%	10—35	MMTCO2E/yr
Extend the life of personal computers by:	50%	25	MMTCO2E/yr
	25%	15	MMTCO2E/yr
Reuse/Recycling			
Increase recycling of construction and demolition debris to:	100%	150	MMTCO2E/yr
	50%	75	MMTCO2E/yr
	25%	40	MMTCO2E/yr
Increase national MSW recycling and composting rate from 2006 rate (32.5%) to:	100%	300	MMTCO2E/yr
	50%	70—80	MMTCO2E/yr
Increase composting of food scraps from 2006 rate (2%) to:	100%	20	MMTCO2E/yr
	50%	10	MMTCO2E/yr
	25%	5	MMTCO2E/yr

Source: EPA, United States Environmental Protection Agency. Opportunities to Reduce Greenhouse Gas Emissions through Materials and Land Management Practices, 2009.

Energy Recovery / Disposal		Estimated GHG Emission Benefit	
Combust percentage of currently landfilled MSW:[65, 66]	100%	70—120	MMTCO2E/yr
	50%	35—60	MMTCO2E/yr
	25%	20—30	MMTCO2E/yr
Combust MSW remaining if national recycling rate is increased to 50%:		65—110	MMTCO2E/yr
Capture percentage of currently emitted methane at U.S. landfills for electricity generation:	100%	150	MMTCO2E/yr
	50%	70	MMTCO2E/yr
	25%	35	MMTCO2E/yr

Source: EPA, United States Environmental Protection Agency. Opportunities to Reduce Greenhouse Gas Emissions through Materials and Land Management Practices, 2009.

3.2 Reducing or avoiding GHG emissions through land management practices

Land management has three key components: land protection, sustainable land use, and land revitalization. Similar to the materials management approaches that can be used in the material flow, land management approaches can be used to reduce GHG emissions by improving practices within or across each of these components. Land protection practices limit how much land is contaminated each year. When land is contaminated, it should be cleaned up to levels protective of human health and the environment.

Sustainable land use practices include those that promote the sustainable use and development of land (including managing land for agricultural and forestry purposes), and minimizing greenfield development. Land revitalization practices promote the cleanup and reuse of contaminated land. By considering the impact of land management throughout its life cycle, this implies significant reductions in GHG emissions. Decisions at the local, or national level related to the cleanup, restoration and/or reuse of contaminated land (i.e., land revitalization) can also reduce GHG emissions.

Many organizations involved with cleaning up contaminated land may find opportunities to employ cleanup techniques that provide an equivalent level of environmental and human health protection while emitting lower amounts of GHGs through:

1. Optimizing remedies and treatment systems both for new and existing remedies;

2. Using alternative energy derived from cleaner and renewable energy sources; and

3. Accounting for the technical needs of potential reuse options and incorporating them throughout the cleanup processes to facilitate sustainable reuse of the property and preservation of greenfields.

Sequestering carbon on these sites is another potential benefit from some cleanup and reuse activities—particularly on former mine lands. At some sites, organic soil amendments can be used to remediate the site, boosting the amount of carbon sequestered in the soil and enhancing vegetation growth. This remediation approach also provides a use for some organic soil amendments such as biosolids which may otherwise be a waste product.

Land cleanup activities may also provide recycling opportunities to further bolster EPA's approaches to materials and land management. For example, reusing and recycling construction and demolition debris from buildings on contaminated land is another effective materials and land management practice; this practice not only reuses both materials and land, but also prevents other land from being used for the disposal of construction and demolition debris.

After cleanup is complete, sustainably reusing land protects the land based carbon sink, by providing sites that can be reused for development, instead of developing greenfields. Reusing these restored properties can also reduce GHG emissions associated with the infrastructure expansion needed to connect newly developed greenfields to already developed areas. Policies that promote land reuse in place of new land development and denser mixed use development—key aspects of smart growth—will avoid the majority of infrastructure and bio-carbon emissions. Sites can also be ecologically restored to increase the amount of undeveloped land and expand the land-based carbon sink. These are some examples of land management approaches that help reduce GHG emissions:

Carbon Sequestration: EPA is studying the potential carbon sequestration that occurs when soil amendments are used to remediate sites.

Land Revitalization: To date, EPA has helped make more than 917,000 acres of previously contaminated lands ready for anticipated use, reducing pressure on greenfields and helping preserve the land-based carbon sink. EPA is promoting the development of renewable energy resources as one particularly promising land revitalization strategy with multiple environmental benefits.

Smart Growth: Smart growth has been shown to reduce household vehicle miles traveled by 20-40% compared with conventional development practices. For example, residents of Atlantic Station, a noted smart growth development, drive an average of 13.9 miles per day, compared to a regional average of 33.7 miles per day.

Green Remediation: Green remediation practices are being employed at contaminated sites, which can reduce GHG emissions. For example, some remediation projects use solar energy to operate ground water pump and treat systems; others are reducing construction engine idling time, and using alternative fuels to reduce GHG emissions.

3.3 Trends in waste generation and management

The long-term vision for the waste sector is to establish a circular global economy in which the use of materials and generation of waste are minimised, any unavoidable waste recycled or remanufactured, and any remaining waste treated in a way that causes least damage to the environment and human health or even creating additional value by recovering energy from waste. To achieve this vision, radical changes to supply-chain management, especially to the product and industrial design part of the supply chain, are needed. Specifically, the 3Rs need to guide industrial design – with implications for materials at all stages – and be overlaid on the entire supply chain. This requirement is, in turn, expected to motivate innovation. The chapter on manufacturing further elaborates on life-cycle approaches, including closed loop and circular systems in manufacturing.

The waste sector is facing three sets of challenges:

1. Increasing growth in the quantity and complexity of waste streams associated with rising incomes and economic growth;

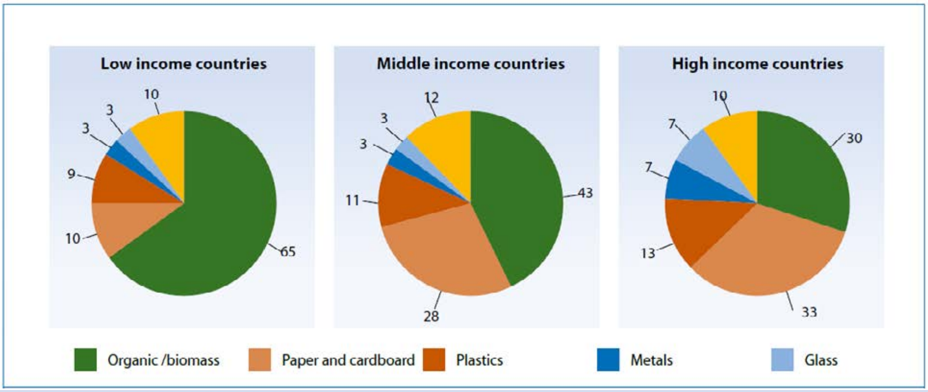
2. Increasing risk of damage to human health and ecosystems; and

3. The sector's contribution to climate change.

The exploitation of the earth's resources continues apace; material use increased eight-fold in the last century (Krausmann et al. 2009). According to the Wuppertal Institute, an average European consumes about 50 tonnes of resources a year, around three times the amount consumed per capita by emerging economies. Furthermore, on average, Europeans dispose twice as much as citizens from emerging economies (Bleischwitz 2009). Per-capita resource use in emerging economies is also increasing considerably while the world's Least Developed Countries (LDC) are beginning the transition towards an industrial type of societal metabolism, as incomes rise and purchasing power is deployed in consumer spending.

Currently, 3.4-4 billion tonnes of municipal and industrial waste are produced every year, of which non-hazardous industrial waste accounts for 1.2 billion tonnes (Chalmin and Gaillochet 2009). A major share of the waste generated is MSW originating from urban settlements (1.7-1.9 billion tonnes, or 46 per cent of the total waste generated) with 0.77 billion tonnes of this being produced by 25 Organisation for Economic Cooperation and Development (OECD) countries alone (UNEP 2010).

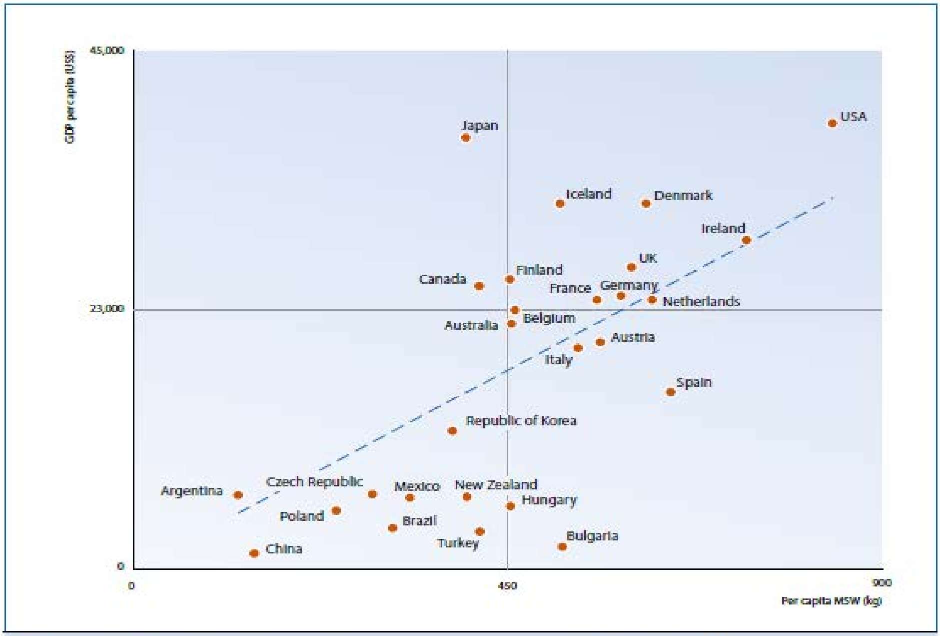
As a country develops and becomes wealthier, the composition of its waste stream typically becomes more varied and complex. The following figure illustrates the high proportion of organic-rich MSW in middle and lower income countries with a gross national income per capita of less than US$ 12,196, while the high-income countries' MSW streams contain a large proportion of paper and plastics.



Composition of MSW by national income

Source: Chalmin and Gaillochet (2009) and averaged

Waste generation is linked to both population and income growth. Of the two, income level is the more powerful driver. The following figure shows the correlation between MSW generation and GDP. In high-income countries, an urban population of 0.3 billion generates approximately 0.24 million tonnes of MSW (0.8 kg per capita per day), while in low-income countries around the same amount (0.26 million tonnes per day) is generated by 1.3 billion people (0.2 kg per capita per day), a quarter of the level high-income countries.



Quadrant	Economic status and waste generation	Country and year of data	
Q1	GDP: More than US$ 23,000 Waste: More than 450 kg per capita	USA: United States of America[a] (2006) IRL: Ireland (2004) DNK: Denmark (2005) ISL: Iceland (2004) GBR: United Kingdom (2004)	NLD: Netherlands (2004) DEU: Germany (2004) FRA: France (2004) BEL: Belgium (2002)
Q2	GDP: More than US$ 23,000 Waste: Less than 450 kg per capita	FIN: Finland (2004) CAN: Canada (2004)	JPN: Japan[e] (2007)
Q3	GDP: Less than US$ 23,000 Waste: Less than 450 kg per capita	BRA: Brazil[b] (2002) ARG: Argentina[c] (2002) CHN: China[d] (2004) POL: Poland (2005)	CZE: Czech Republic (2005) MEX: Mexico (2006) KOR: Republic of Korea (2002) NZL: New Zealand (1999) TUR: Turkey (2004)
Q4	GDP: Less than US$ 23,000 Waste: More than 450 kg per capita	AUS: Australia (2002) HUN: Hungary (2004) BGR: Bulgaria[f] (2003)	ITA: Italy (2004) AUT: Austria (2004) ESP: Spain (2004)

Note: US$ 23,000 represents the median point in the GDP data.

GDP per capita vs. MSW per capita[1]

Source: MSW data source from a EPA (2007), b Borzino (2002), c Methanetomarkets (2005), d World Bank (2005), OECD (2008) and e Yatsu (2010) and f GHK (2006); Population data available at http://esa.un.org/wpp/; GDP data sourced from World Bank.

The figure below shows estimates of MSW generation in different parts of the world. It rose in the US and the EU by 21 per cent and 14 per cent respectively from 1995 to 2007. However, due to increased awareness and policy interventions addressing waste management (for example, EU regulations stimulating recycling of obsolete vehicles since 2000 and electrical and electronic waste since 2002), the rate of MSW generation slowed in the EU and (to a lesser extent) in the US in the period from 2003 to 2007. The linkage between affluence and waste generation remains quite strong, in spite of improvements in efficiency, and represents a significant challenge for developing countries as they become wealthier, particularly in Asia (World Bank 1999).

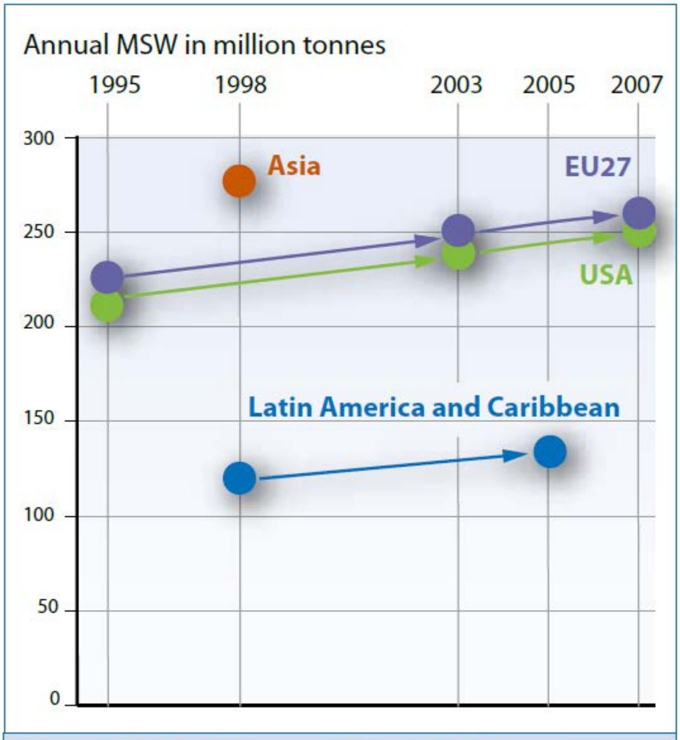


Figure 4: Estimated generation of MSW across regions of the world

Source: Acurio et al (1998), World Bank (1999), EPA (1999) and (2009), Hoornweg and Giannelli (2007) and Eurostat (2010)

At best, relative decoupling has begun in OECD countries, with a stabilisation of per-capita waste generation in the last decade, as shown in the next figure. The recent awareness on benefits of waste minimisation, but also the shifting of waste-intensive production to developing and emerging countries may have contributed to this development. Landfill remains the predominant method of disposal in these countries (OECD 2008).

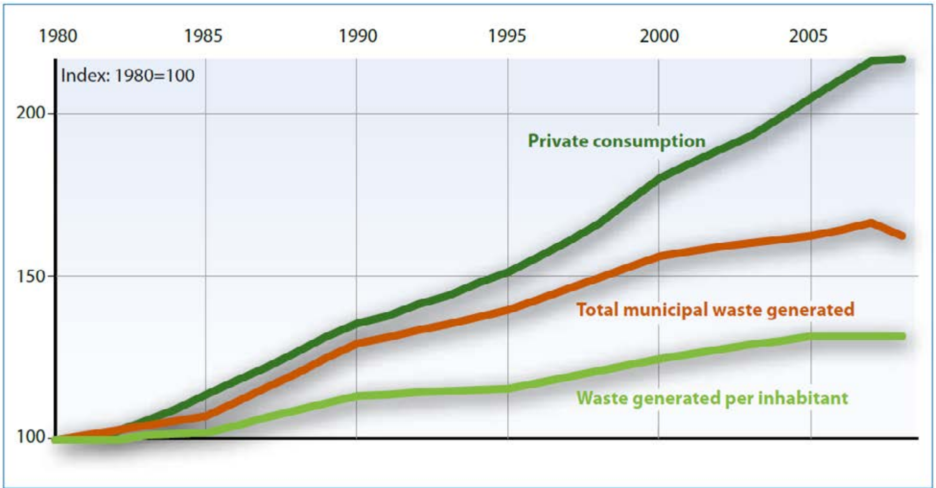


Figure 5: Relationship between private consumption and municipal waste in OECD countries
Note: The indicators presented here relate to amounts of municipal waste generated. They show waste generation intensities expressed per capita and per unit of private final consumption expenditure (which excludes public expenditures on education, health and similar categories) in 2006, and related changes since 1980.

Source: OECD (2008).

The rapid pace of industrialisation around the world has brought about increasing demand for metals, which are considered as core raw materials for infrastructure and manufacturing of products. The demand for metals is expected to maintain dynamic in the future: in developing countries due to economic growth, and in industrialized countries due to modern technologies with dissipative metal applications. Since metals are a finite resource, the potential challenge on metal supply could be addressed through recycling across the life-cycle.

Among the various steps of the metal life-cycle, societal or in-use metal stocks, which include all metals put into use and currently providing service, are the most relevant metal stocks to focus. On a global level, most of the world’s in-use stocks reside in more developed countries. For instance, Japan and the United States posses the highest in-use stocks and exceed the value of China by 9 and 13 times. Moreover, data suggests that per capita inuse stocks in more-developed countries typically exceed those in less-developed countries by factors of 5 to 10.

One of the key strategies in meeting this increasing demand is to take advantage of anthropogenic mines, or urban stocks, which has a great potential to reduce dependency on virgin metal resources and mitigate the environmental degradation caused by mining activities. However, tremendous weak points have been found in global metal recycling. For instance, mass-scale use of specialty metals like gallium, indium, etc, in the last three decades and the lack of infrastructure for recycling in many developing countries has led to dissipative losses of such metals.

Thus, the recycling rates for some of the metals, especially specialty metals are relatively low. It has been recognized that creating a circular economy is key for increasing metal needs of the future. Setting of appropriate metal recycling infrastructure and services in urban areas - that are tomorrow's metal mines – is essential and should be given high priority.

The International Resource Panel decisively states that it is important to enhance capacity building, technology transfer and international cooperation in developing countries through international recycling conferences, technological implementation programmes and specific scientific exchange programmes.

The Panel also highlights three key issues that require urgent attention:

- Research & development. Data acquisition and analysis, recycling technologies research, and other research and development efforts should be a priority in the development process. Global data on a large variety of metals on equal spatial and temporal resolution is actually not available
- Stopping illegal waste transport. International organisations like UNEP and OECD have to multiply their engagement in the monitoring and controlling of illegal scrap exports.
- Continuous improvements of legislative systems. The more developed countries should reinforce their attempts to help the less developed countries install appropriate legislative systems and ensure their enforcement in order to take advantage of metal stocks in society.

Waste volumes are not necessarily the most important challenge ahead. Mixed MSW, hazardous health-care waste, and industrial waste streams can impose serious health and ecological risks if these wastes remain uncollected or dumped in uncontrolled and unsecured landfill sites. In low income countries, for example, collection rates are lower than 70 per cent, with more than 50 per cent of the collected waste disposed through uncontrolled landfilling and about 15 per cent processed through unsafe and informal recycling (Chalmin and Gaillochet 2009). Given the amount of valuable components in MSW, the mixing of wastes also means a lost opportunity to recover components that could be recycled and used as new resources.

3.4 Climate impact of waste management practices

Every waste management practice generates GHG, both directly (i.e. emissions from the process itself) and indirectly (i.e. through energy consumption). However, the overall climate impact or benefit of the waste management system will depend on net GHGs, accounting for both emissions and GHG savings.

3.4.1 Landfill

In the majority of countries around the world, controlled and uncontrolled landfilling of untreated waste is the primary disposal method. Methane emissions from landfill represent the largest source of GHG emissions from the waste sector, contributing around 700 Mt CO_2-e (estimate for 2009) (Bogner et al 2007). In comparison, the next largest source of GHG emissions from the management of solid wastes is incineration, estimated to contribute around 40 Mt CO_2-e (2009 data estimated in Bogner et al (2007)). Landfills may also be a source of nitrous oxide; however the contribution to global GHG emissions is believed to be negligible, and related to the management of both wastewater biosolids disposed at landfills and landfill leachate (Bogner et al 2008).

The next table provides a qualitative summary of the indirect and direct GHG emissions and savings associated with landfilling. To provide a complete picture, all GHGs are noted, including biogenic CO_2.

Summary of indirect and direct GHG emissions and savings from landfills (adapted from Scheutz et al 2009)

Upstream (indirect)	Direct (operating)	Downstream (indirect)
CO_2, CH_4, and N_2O emissions from: production of fuel used on site, electricity consumption, and production of materials (i.e. liner material, soils)	Fugitive emissions of CH_4, trace NMVOC[9], N_2O and halogen-containing gases; biogenic CO_2 from waste decomposition; CO_2, CH_4, N_2O, trace CO and NMVOC from fuel combustion in equipment; biogenic CO_2, CO_2, CH_4, and N_2O from leachate treatment	Energy produced from combustion of captured LF CH_4 substitutes fossil energy: avoided CO_2 Long-term carbon stored in landfill (organic materials largely recalcitrant in anaerobic conditions): avoided CH_4 and biogenic CO_2

NMVOC refers to non-methane volatile organic compounds.

Source: UNEP. Waste and Climate Change Global Trends and Strategy Framework.

There are several general points worth noting regarding landfills and GHG emissions in the non-OECD region:

- Where landfill practices are informal and do not extend to site compaction and cover, the optimum anaerobic conditions for methane-production do not develop. Therefore less methane is produced per tonne of organic waste (compared to controlled sites). Degradation processes proceed under more aerobic conditions, generating larger quantities of biogenic CO_2.

- There is a trend towards more managed landfill practices in developing nations, which will somewhat ironically lead to enhanced anaerobic conditions and therefore generation of greater quantities of methane in the future. However, higher methane generation does mean that landfill gas capture systems become more economically viable.

Landfills reduce GHG emissions where landfill gasses (LFG) recovery systems generate energy that substitutes for fossil-fuel energy sources, or where carbon storage is taken into account. In terms of energy savings, the climate benefit calculated for a specific site will largely depend on the type of fuel source of the energy that is assumed to be replaced. Monni et al (2006) compared potential emissions savings on a global scale for landfill methane projections in 2030, and estimated 56 Tg CO_2-e where coal-derived energy is assumed to be replaced and 22 Tg CO_2-e where natural gas-derived energy is replaced (natural gas is a 'cleaner' fuel than coal, therefore there is less climate benefit in replacing natural gas).

Over a 100-year period, managed landfills of the type seen in developed countries may capture around 50 – 80% of methane generated (Manfredi et al 2009, Bahor et al 2009). Landfills in economies in transition regions are estimated to capture around 35% of methane generated.

Certain waste materials are largely recalcitrant in landfills – non-biodegradable materials (i.e. plastics), lignin and some lignin-bound cellulose and hemi-cellulose undergo minimal decomposition in the anaerobic conditions within managed landfills (Barlaz 2006). A high proportion of wood waste, for example, may be considered as carbon stored in landfills while anaerobic conditions prevail. It must be emphasized that, purely from a climate change perspective, burying wood in landfills may be part of the solution; however, there are myriad other reasons (i.e. ecological, resource use, land use) for not doing this.

Diversion of organic wastes from landfill and implementation of active systems for landfill gas extraction are complimentary to an extent: due to the gradual release of methane over many years, even if a ban on landfilling organic waste were implemented at a site today, there would still be an existing store of organic material releasing methane, that could be extracted into the future.

Landfills may currently represent the largest source of GHG emissions from the waste sector, but the options for reducing this climate impact are available and achievable: divert biodegradable waste from landfill disposal and maximise landfill gas capture. Neither option is technically complex, and there is a body of knowledge and experience in OECD regions that could be transferred to non-OECD countries.

3.4.2 Thermal treatment

Thermal waste treatment refers to mass-burn incineration, co-incineration (i.e. replacing fossil fuels with refuse-derived fuel (RDF) in conventional industrial processes, such as cement kilns), pyrolysis and gasification. Mass-burn incineration is the most commonly applied thermal treatment. Pyrolysis and gasification may be considered as emerging technologies, with limited success in treating mixed waste streams. The majority of studies assume that energy is recovered from the thermal treatment of waste, either as heat or electricity, which can equate to a considerable GHG saving (depending on the type of energy displaced). Metals are also recovered from incinerator ash, and this contributes to further GHG benefits.

Approximately 130 million tonnes of waste are currently incinerated across 35 countries (Bogner et al 2007). Japan, Denmark, and Luxembourg treat >50% of the waste stream through incineration. France, Sweden, the Netherlands and Switzerland also have high rates of incineration (Bogner et al 2007). Incineration is only applied in a limited capacity in the remainder of the OECD countries. There is no incineration of mixed waste practiced in either Australia or New Zealand, largely due to public opposition. Australia, New Zealand, Canada and the US do not have legislation in place that limits landfilling (i.e. as is the case with the EU Landfill Directive); therefore landfill remains the cheapest and thus preferred disposal option. Incineration of mixed wastes is a largely unfeasible option in non-OECD countries due to cost and often unsuitable waste composition.

At the global level, the climate impact of incineration is minor compared to that of landfilling, contributing around 40 Mt CO_2-e in the current year (Bogner et al 2007). Typically only fossil CO_2 is counted as a GHG emission from incineration; therefore, the overall climate impact of incineration will be highly influenced by the fossil carbon content of the input waste. Downstream, indirect GHG savings due to energy generation may dominate an estimate of emissions from incineration, depending on the energy assumed to be replaced. The next table provides a qualitative summary of the indirect and direct GHG emissions and savings associated with incineration. To provide a complete picture, all GHGs are noted, including biogenic CO_2.

Thermal technologies could have a valuable role to play in the treatment of specific streams of wastes, or carefully prepared mixed residual wastes, as part of an integrated and future-thinking waste management system. In many countries, thermal treatment plants require long lead-times (i.e. >10 years) to meet planning approval, financing, construction, and commissioning. In addition, facilities will last for at least 25 years with limited flexibility for changing waste supply, which suggests that capacity needs to be planned for carefully. This suggests that such facilities may be part of a longer-term strategy for climate abatement.

Summary of indirect and direct GHG emissions and savings from incineration (adapted from Scheutz et al 2009)

Upstream (indirect)	Direct (operating)	Downstream (indirect)
CO_2, CH_4, and N_2O emissions from: production of fuel used in facility, heat and electricity consumption, production of materials (i.e. air pollution control (APC) systems) and infrastructure	CO_2 and biogenic CO_2 from waste combustion; trace CH_4, N_2O, CO, and NMVOC	Heat and/or electricity produced from combustion of waste substitutes fossil energy: avoided CO_2 Recovery of metals from ash substitutes raw materials: avoided GHG emissions from material production Use of bottom ash to substitute aggregate: avoided GHG emissions from producing virgin aggregate CO_2, CH_4, N_2O, and trace CO, and NMVOC from transport of APC residues and fly ash

Source: UNEP. Waste and Climate Change Global Trends and Strategy Framework.

3.4.3 Mechanical biological treatment (MBT)

MBT refers to a wide range of technologies that separate incoming waste into recyclable materials for recovery and an organic fraction for biological treatment (stabilisation). In Europe, facilities tend to produce a refuse-derived fuel (RDF) for subsequent thermal treatment; this is not the case in other regions (i.e. Australia). MBT – in all its various configurations – has a strong track record in Europe, and the UK and Australia are increasingly embracing MBT as the cost of landfilling increases in these countries. MBT is relatively scarce in the rest of the world, therefore the majority of LCA-type studies that estimate GHG emissions from MBT are based on European, UK, and Australian conditions.

The downstream, indirect GHG emissions/savings from MBT generally outweigh both upstream and direct process emissions. The following table provides a qualitative summary of the indirect and direct GHG emissions and savings associated with MBT. To provide a complete picture, all GHGs are noted, including biogenic CO_2.

The overall climate impact of a particular MBT technology will depend on:

- The efficiency of front-end sorting processes – recovered materials contribute to potentially significant downstream GHG savings
- Energy consumption of system – more automated, sophisticated systems have a higher energy demand
- Energy generation – in the case of anaerobic digestion (AD)-type MBT facilities, energy produced from biogas – either heat or electricity – will account for a GHG saving
- Control of emissions during the maturation phase – best-practice for MBT involves the use of air pollution control systems, such as scrubbers and biofilters, to prevent emissions of nitrous oxide and methane
- Carbon storage potential – compost derived from mixed waste is usually restricted in application (i.e. remediation of contaminated land or landfill), but may be credited with a GHG benefit from carbon storage
- Biodegradability of final output – the biodegradability of the final composted output will decrease with increased maturation time, and the lower the biodegradability, the less potential for the material to generate methane (if landfilled)

Summary of indirect and direct GHG emissions and savings from MBT (adapted from data provided in Scheutz et al 2009)

Upstream (indirect)	Direct (operating)	Downstream (indirect)
CO_2, CH_4, and N_2O emissions from: production of fuel used in facility, heat and electricity consumption, and infrastructure	CO_2, CH_4, N_2O, trace CO and NMVOC from fuel combustion in equipment	Heat and/or electricity produced from combustion of biogas substitutes fossil energy (MBT AD): avoided CO_2
	Biogenic CO_2, CH_4, and N_2O from windrows	
	Biogenic CO_2, CH_4 (leakages) and trace N_2O from reactors, and biofilters (MBT AD)	Front-end recovery of materials substitutes raw materials: avoided GHG emissions from material production
		Use of organic compost output to substitute soil growth media: avoided GHG emissions from producing virgin growth media
		Long-term carbon stored in landfill (organic materials largely recalcitrant in anaerobic conditions):avoided CH_4 and biogenic CO_2

Source: UNEP. Waste and Climate Change Global Trends and Strategy Framework.

MBT, with simple aerobic composting of the organic portion of the mixed waste stream, may offer an easy, relatively inexpensive solution to reduce the climate impact of landfilling waste. This may also be seen as an interim solution to gain rapid GHG benefit while waste management systems are improved (i.e. to increase source separation and recovery).

3.4.4 Composting and anaerobic digestion

Composting systems treat biodegradable material such as food, animal industry wastes, green waste, wood, and agricultural residues and produce a range of organic soil amendment products that can replace manufactured fertilisers and/or peat, reduce the need for pesticides, improve soil structure, reduce erosion, and reduce the need for irrigation. Around 2,000 composting facilities currently treat source-separated household organic waste in Europe (Boldrin 2009). Composting and anaerobic digestion of source-separated wastes requires significant investment in local community education (both households and commercial enterprises) and public awareness – this is essential to ensure proper source-separation, highquality compost products, and secure end-use markets. Simple composting systems are an effective, low-tech solution for developing countries to reduce waste quantities and generate a valuable compost product for application to agriculture.

The climate impact of composting and AD systems is due to both direct process emissions and indirect upstream and downstream emissions. The next table provides a qualitative summary of the indirect and direct GHG emissions and savings associated with composting and AD processes. To provide a complete picture, all GHGs are noted, including biogenic CO_2.

Summary of indirect and direct GHG emissions and savings from composting and AD processes (adapted from data provided in Scheutz et al 2009)

Upstream (indirect)	Direct (operating)	Downstream (indirect)
CO_2, CH_4, and N_2O emissions from: production of fuel used in facility, heat and electricity consumption, and infrastructure	CO_2, CH_4, N_2O, trace CO and NMVOC from fuel combustion in equipment **Compost processes**: Biogenic CO_2, CH_4, and N_2O from windrows **AD processes**: Biogenic CO_2, CH_4 (leakages) and trace N_2O from reactors, and biofilters	Heat and/or electricity produced from combustion of biogas substitutes fossil energy (**AD processes only**): avoided CO_2 Use of organic compost output to substitute soil growth media: avoided GHG emissions from producing virgin growth media

Source: UNEP. Waste and Climate Change Global Trends and Strategy Framework.

Direct emissions from composting facilities result from fuel combustion in equipment (i.e. frontloaders) and from decomposition of the organic material. As composting produces CO2 from biogenic carbon sources, it does not contribute to national GHG inventories for the waste sector under IPCC accounting methods (IPCC 2006). CH_4 and N_2O emissions will depend on the type of organic waste input, the technology used (in particular, whether the process is open or enclosed), and how the process is managed (Boldrin et al 2009).

Once compost is applied to land, further, minimal emissions will be generated as organic compounds are gradually mineralised to biogenic CO_2. Therefore, compost applied to soil has a medium or long-term potential to store carbon; however, it does not represent a permanent solution for 'locking-up' carbon (Smith et al 2001; Favoino and Hogg, 2008). Quantifying the climate benefit of carbon storage is extremely difficult and will largely depend on how the soil landscape is managed (cropping, tillage, irrigation, compost application rate, etc), climate, and original carbon content of the compost and soil.

Anaerobic digestion (AD) of source-separated organic wastes is an alternative to aerobic composting systems; although AD tends to accept a smaller range of materials (i.e. materials with a high lignin content, such as woody garden wastes, are generally not suitable for AD in large quantities). The biogas produced by AD tends to have a high methane content (around 60%, although it will depend on the process parameters) and therefore high energy content.

Depending on facility performance, assumptions regarding energy, the end-use of energy generated, and assumptions regarding use of digestate, an advanced, European-style AD facility may have a net climate impact ranging from -375 to 111 kg CO_2-e per tonne of wet organic waste input (Møller et al 2009). Higher levels of biogas production, a high-CO_2-e energy mix, and use of heat rather than electricity would all contribute to greater GHG savings.

3.4.5 Recycling

After waste prevention, recycling has been shown to result in the highest climate benefit compared to other waste management approaches. This appears to be the case not only in the OECD (i.e. ISWA 2009, Christensen et al 2009, US EPA 2006) but also in developing countries (i.e. Pimenteira et al 2004, Chintan 2009), although limited data is available. For example, in the US, recycling materials found in MSW resulted in the avoidance of around 183 Mt CO_2-e in 2006 (US EPA, 2009). Estimates of GHG savings are generally based on the premise that recycled materials replace an equal – or almost equal – quantity of virgin materials in a closed-loop recycling system (i.e. where material is reprocessed back into the same or a similar product). Industrial symbiosis involves the exchange of resources including by-products among industrial enterprises, which may form 'recycling clusters' to facilitate sharing resources.

The next table provides a qualitative summary of the indirect and direct GHG emissions and savings associated with recycling processes. To provide a complete picture, all GHGs are noted, including biogenic CO_2.

Summary of indirect and direct GHG emissions and savings from recycling processes (adapted from data provided in Scheutz et al 2009)

Upstream (indirect)	Direct (operating)	Downstream (indirect)
CO_2, CH_4, and N_2O emissions from: production of fuel used in facilities (i.e. material recycling facilities and reprocessing plants), heat and electricity consumption, and infrastructure	CO_2, CH_4, N_2O, trace CO and NMVOC from fuel combustion in equipment	Recovery of materials substitutes raw materials: avoided GHG emissions from material production Recovery of paper avoids use of harvested wood: wood biomass replaces fossil fuel as energy source (biogenic CO_2 emissions replace fossil CO_2) or unharvested wood sequesters carbon

Source: UNEP. Waste and Climate Change Global Trends and Strategy Framework.

A recent investigation by the UK Waste and Resources Action Programme (WRAP) of 55 LCA studies found that 'across the board, most studies show that recycling offers more environmental benefits and lower environmental impacts than other waste management options' (WRAP, 2006). The report's main GHG-related conclusions for specific materials included:

- On average, virgin production of paper followed by incineration with energy recovery consumes twice as much energy as paper recycling; however, the GHG benefit of recycling paper depends largely on the system boundaries adopted by the individual LCA studies (in particular, whether the GHG 'cost' of using timber to produce paper is accounted for)

- Closed-loop recycling of glass results in net climate benefits compared to incineration. There is insufficient data on open-loop recycling (i.e. glass recycled into aggregate, insulation, or other secondary product) to determine the net GHG impact
- - Where recycled plastic replaces virgin plastic of the same kind in ratio of 1:1 (by weight), recycling of plastic was found to have a net environmental benefit compared to incineration. For every kg of plastic recycled, around 1.5 – 2 kg CO_2-e is saved.
- Production of virgin aluminium requires 10-20 times more energy than recycling aluminium. Although regional differences in energy sources cause large variations in the extent of GHG savings, there is a universal climate benefit in recycling aluminium.
- Production of virgin steel requires around two times as much energy as production of steel from recycled scrap. As above, regional differences in energy sources may cause variations in the extent of GHG savings; however there is a universal climate benefit in recycling steel.

The role of the informal recycling sector should not be underestimated in developing nations. The World Bank estimates that around 1% of the urban population in developing countries (approximately 15 million people) earns their livelihood from waste-picking and the informal recycling sector (Medina 2008).

The economic contribution of waste pickers should also not be overlooked. Informal recycling in Jakarta reduces the volume of waste by approximately 30%, thereby saving on collection and disposal costs, and extending the life of landfills (Medina 2008). In major Indian cities such as Delhi and Bangalore, waste pickers prevent at least 15% of MSW going to landfill, saving the government around US$13,700 per day in waste collection and disposal costs (Sharholy 2008). Mexican paper mills have strengthened relationships with waste picker associations in order to secure more supply of valuable waste paper.

3.5 Waste prevention

Waste prevention is considered the most important action in the waste hierarchy; however it often receives minimal priority in terms of resource allocation and effort. Waste avoidance is critical to decoupling waste generation from economic growth. Within waste prevention there exists a raft of mechanisms that can deliver climate benefit, such as cleaner production, extended producer responsibility, sustainable consumption and production, etc. The SCP Branch of UNEP is involved in a number of programmes targeting sustainable consumption and production, including collaborations with the International Solid Waste Association (ISWA) on waste minimisation. Various mechanisms have been developed and applied to prevent waste arising, with most relying on concerted efforts to educate waste generators.

Since the early 1990s, the EU has been actively developing waste-related policy measures. The following EU Directives and Strategies have been instrumental in greening the region's waste management industry: Packaging (1994), Waste Communication Strategy (1996), Landfill (1999), End of Life Vehicles (EoLV 2000), Waste Electrical and Electronic Equipment (WEEE 2002), the Thematic Strategy on Waste Prevention and Recycling of Waste and Sustainable Use of Natural Resources (2005), the EU's revised Waste Framework Directive (2008) and the Raw Material Initiative (2008).

Meeting the 85 per cent EoLV target by 2006 had the potential to reduce the landfilling cost for the EU by € 80 million per year, which is a cost saving of 40 per cent, compared to the cost that prevailed prior to the directive. Meeting the 95 per cent target by 2015 will reduce the cost further by 80 per cent (GHK and Bio Intelligence Service 2006).

Individual countries have also moved forward with waste related regulations and their enforcement. The German Packaging Ordinance introduced in 1991 helped encourage recycling of packaging waste which is collected through a third party organisation. British Columbia Recycling Regulation of 2004 brought about a considerable increase in the proportion of recycled waste in Canada.

Developing-country examples include the Law of the People's Republic of China on the Prevention and Control of Solid Waste Pollution adopted in 1995, South Africa's National Waste Management Strategy in 1999, India's Municipal Waste Management and Handling Rules in 2000, the Philippines's Ecological Solid Waste Management Act in 2000, Malaysia's Solid Waste and Public Cleansing Management Act in 2007 and

Indonesia's Act regarding Waste Management in 2008. Although the real effects of such measures will come from implementation, the existence of these instruments provides a signal of political commitments to greening the waste sector.

In terms of climate change impact, the benefits of waste prevention generally outweigh benefits derived from any other waste management practice: not only are net GHG emissions avoided from treatment and disposal of the waste, but there is also a noteworthy benefit in avoided GHG emissions from less raw resource extraction and manufacturing.

A US EPA study found that, generally, the net GHG emissions for a given material are lowest for source reduction and highest for landfilling (US EPA, 2006). This is especially true for prevention of paper waste where GHG savings are attributed to increases in forest carbon sequestration (i.e. less use of virgin forest materials to produce paper products equates to less deforestation). A recent report produced by the US EPA Office of Solid Waste and Emergency Response (US EPA 2009) examines how GHG emissions could be prevented through alternative management of materials (US EPA, 2009). An estimated 42% of total US GHG emissions are due to materials management. Strategies discussed in the report include source reduction through improved product design and cleaner production, increasing product durability, and maximising the ease of product disassembly (for recycling).

3.5.1 European Union: The Landfill Directive

Issued in 1999, the Landfill Directive was a milestone in EU waste policy. It marked a decisive shift from landfill towards the EU's new waste hierarchy, which prioritizes waste prevention, followed by re-use, recycling and recovery, and seeks to avoid landfilling wherever feasible.

Determining the extent to which EU policies have effected change in national waste management practices is a complex task. The process of diverting biodegradable municipal waste from landfill commenced at different times in the countries and region studied and has proceeded at varying speeds. In addition, urbanization and population density are obviously important socio-economic drivers for diverting waste from landfill.

The Landfill Directive's success is based on two core factors. First, its combination of long-term and intermediate targets has provided a good framework for countries to landfill less biodegradable municipal waste. In particular, the targets have helped governments and the European Commission measure progress and keep attention on the core issues. Second, the directive's flexibility has been an important asset, affording Member States the space to try out alternative policies, adjust measures to match national and regional realities (including existing waste management practices, institutional structures and environmental conditions), and adapt policies in the light of experience. Evidently, the Landfill Directive has had the greatest impact in locations where the process of shifting away from landfill was not already under way.

The strategies usually include a combination of recycling, incineration, and/or mechanical-biological treatment:

- Closing landfills is an important driver for adopting new waste treatment options. The number of landfills in the countries and region studied decreased significantly in the last 10–15 years, mostly through the closure of dumpsites and other low standard sites. Although this probably implies a reduction in total landfill capacity, data on current waste generation and landfill rates indicate that existing capacity in most countries is sufficient for many years to come.
- Incineration capacity has increased significantly as governments have tightened emissions standards.
- Separate collection of biodegradable municipal waste fractions (mainly paper and cardboard, packaging waste, and food and garden waste) is increasingly used to divert biodegradable waste from landfill.
- Mechanical-biological treatment is used as an alternative option to incineration to treat mixed municipal waste, in fact capacity for mechanical-biological treatment has doubled or tripled in some countries. The countries studied that use this treatment option all use or are planning to use dedicated incineration and co-incineration of the refuse-derived fuel produced to generate energy.
- Since 1999, capacity at composting and anaerobic digestion plants has increased in most countries.
- If composting is to play a role in diverting waste from landfill then a well-functioning market for compost is needed. This in turn necessitates that the products of biological treatment of biowaste are of good quality.

To comply with the provisions of the Landfill Directive, countries have introduced various measures to increase the cost of landfilling. The increasing gate fees mainly result from rising technical standards for landfills and implementation of the principle that gate fees should cover all costs involved in the setting up, operating and closing landfills.

It is important to note that when governments and competent waste management authorities set waste management objectives and targets these must be clearly defined. Governments also need to designate clearly the institutions and actors responsible for meeting them. Cooperation between municipalities or larger geographical units such as provinces or districts plays an important role in ensuring that necessary financial and human capacity is available to develop alternatives to landfill.

An often overlooked problem in waste recycling is the lack of acceptance of waste-derived products among potential users. Lack of public acceptance is also very often an obstacle for the introduction of waste incineration. People have tackled incineration's poor reputation in the past by setting ambitious emission standards. Policy measures and instruments that the public traditionally regards positively; for example separate collection of waste paper, can be further strengthened. In addition, regular communication activities are important to keep households and others aware and active in separating waste and participating in home composting schemes.

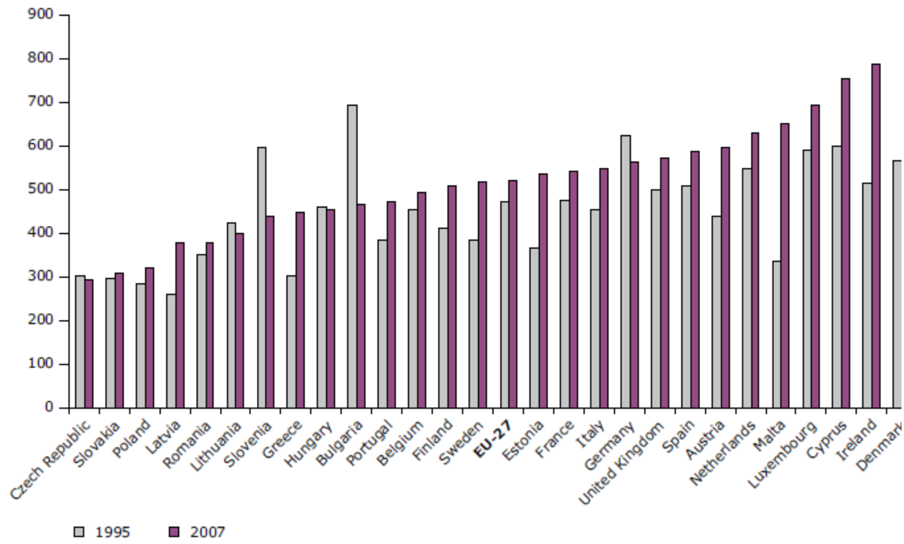
3.5.2 Waste management in the EU-27

The Sixth Environment Action Programme (2002–2012) sets out the EU's key environmental objectives. One of the overall goals is to decouple resource use and waste generation from the rate of the economic growth. The programme also targets a significant, overall reduction in the volumes of waste generated through waste prevention initiatives and a significant reduction in the quantity of waste going to disposal. It further encourages reuse and aims to reduce the level of hazard, giving preference to recovery and especially recycling, making waste disposal as safe as possible, and ensuring that waste for disposal is treated as close as possible to its source.

According to the new Waste Framework Directive (2008/98/EC), the European Commission will propose measures to support waste prevention activities, e.g. by setting prevention and decoupling objectives for 2020. Also by 2020, at least 50 % of waste materials such as paper, glass, metals and plastic from households and possibly from other origins must be recycled or prepared for re-use. The minimum target set for construction and demolition waste is 70 % by 2020.

On average (unweighted), the European citizen generated 10 % more waste in 2007 than in 1995 (Eurostat). The waste volume grew even faster (11.5 %) in the EU-15 Member States. As the next figure illustrates, these aggregated figures mask considerable differences between Member States.

Generation of municipal waste in the EU-27, 1995 and 2007



Source: Eurostat Structural Indicators

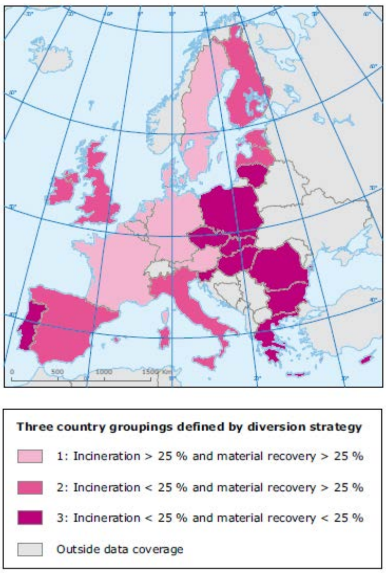
3.5.3 Development of municipal waste management

Broadly speaking, Member States can be categorised under three waste management 'groupings', clustered according to their strategies for diverting municipal waste away from landfill and their relative shares of landfilling, material recovery (mainly recycling and composting) and incineration (EEA, 2007a).

The first grouping comprises countries that maintain high levels of both material recovery and incineration, and have relatively low landfill levels. Countries in this group generally introduced several policy instruments early, often before the adoption of Directive 94/62/EC on packaging and packaging waste (hereinafter referred to as 'the Packaging Directive') and the Landfill Directive.

The second grouping brings together countries with high material recovery rates and medium levels of incineration, and with a medium dependence on landfill. In general countries in this grouping introduced policy instruments after adopting the Packaging Directive in 1994, and the Landfill Directive in 1999.

Three country groupings defined by diversion strategy



Source: EEA, European Environment Agency. Diverting waste from landfill — Effectiveness of waste-management policies in the European Union. 2009.

The third grouping contains those countries whose material recovery and incineration levels are both low and whose dependence on landfill is relatively high. This group comprises the majority of the EU-12 Member States in the process of implementing EU regulations and several, but not all Member States with a 4-year derogation from the Landfill Directive (i.e. Bulgaria, the Czech Republic, Greece, Lithuania, Poland, Romania, Slovakia and the United Kingdom) or from the Packaging Directive (Greece and Portugal). The geographical distribution of the three groupings is shown in this figure:

4 MANAGEMENT AND MINIMIZING OF LANDFILL GAS EMISSIONS

Landfill can be defined as "a site for the disposal of waste materials, depositing waste underground or on the surface for periods of time longer than one year for non-hazardous waste, and exceeding six months for hazardous waste."

From a technical point of view, waste disposal is defined as the ordered deposition of waste at locations properly built and prepared, following the corresponding environmental requirements. Waste disposal is the last option in the hierarchy of waste contained in the European Union management principles.

At the policy level, the general trend is to reduce landfill disposal, especially bio-recyclable materials (fully optimize waste resources), and to control environmental contaminants (pollutants in the atmosphere, leachate generation and treatment, distinction in the discharge of hazardous waste, inert or non-hazardous waste, etc..).

The characteristics of landfills depend on the methods of operation and management, as well as the main characteristics (waterways, water bodies and agricultural and urban areas, the existence of groundwater or natural reserves, geological and hydrogeological conditions, risks of flooding, subsidence, earth movement or landslides, protection of cultural heritage of the area where they will be located) and consider the distances between the boundary of the site and residential and recreational areas.

The following table shows the subdivision of the different types of waste-household origin in the different treatment streams. See the table below:

T/YEAR RATIO AND PERCENTARGE OF WASTE OF EACH FLOW TREATMENT OF MSW IN SPAIN.

Treatment system	t/year	%
Controlled waste	14.696.000	59,35
Triage + Composting	6.455.000	26,07
Incineration	1.915.000	7,73
Selectively collected packaging waste	331.000	1,33
Selectively collected organic waste	244.000	0,98
Triage + methanation	1.124.000	4,54
TOTAL	2.4765.000	100,00

Source: Spanish Ministry of Agriculture, Food and Environment, 2006.

4.1 Closure of landfills

A landfill may be considered sealed only if the competent authorities perform a final on-site inspection, assessing all the reports submitted and notifying the operator its approval for the closure. Then, the entity will be responsible for its maintenance; monitoring and control during the period required by the relevant authorities and in no case shall be less than 30 years.

This entity will also be responsible for monitoring and analyzing landfill gas and leachate, and the groundwater regime in the vicinity of the site. After the useful life of a landfill is over, it is important to consider the restoration of the area occupied. This restoration should be done with all environmental safeguards.

These are the stages for closure and landfill restoration:

1. Conduct a detailed site survey, in order to write a proper sealing project, as each landfill has particular characteristics.

2. Write the sealing project.

3. Once the landfill has received its final shipment of waste, it is still performed an access control, in order to prevent further discharges.

4. Conditioning discharge surfaces.

5. Sealing covers, used as a barrier to isolate the waste, prevent the filtration of river water and close the outlet passage of the vent gases through the exhaust system of gas. This includes revegetation of the surface. Sealing layers:

   - The top layer of waste is covered with a 0.5 m compacted clay mineral layer.
   - Layer of high density polyethylene (HDPE) that is covered by a geotextile.
   - Gravel drainage layer (not <50 cm), enabling the collection and channeling of rainwater.
   - Capa de tierra de 1m de espesor y de naturaleza adecuada a la vegetación que se prevea.
   - 1m thickness soil layer suitable for the vegetation.
   - Humus soil fertilized with appropriate vegetation to these conditions.

6. Control surface runoff to reduce the infiltration of water runoff flowing and decreasing landfill leachate production.
7. Control leachate extraction placing drainage systems leading to leachate storage ponds.
8. Controlling the extraction of gases and avoid its uncontrolled migration.
9. Monitoring of gas and leachate management during a period of 30 years after closure.
10. Protective measures to avoid possible effects in other areas.
11. Waste and soil treatment, as it must be conditioned for revegetation and reclamation.

4.2 Post-closure maintenance

4.2.1 Production of biogas

The absence of oxygen in a landfill favours anaerobic digestion of biodegradable waste producing gases such as methane, carbon dioxide and water vapor mainly, and other volatile organic compounds (hydrogen sulfide, ammonia, pectins, mercaptans, etc.)..

The volume and composition of gases generated depends, not only on the content of the organic waste disposal but also on the moisture, and the degree of waterproofing of the landfill.

Gas production is automatically controlled by the gas conduction to control stations which determine parameters such as flow, pressure and temperature. These data are centralized in a control center using a computerized system.

4.2.2 Exploitation of landfill biogas

The recovery of methane gas at a landfill, municipal waste involves the following actions:

- Preparation of wells or chimneys

Essential conditioning to hinder the introduction of air through the surface adjacent to each well, estimated at 15-20 m radius (area of influence from the aspiration). It basically consists of the isolation of the area adjacent to each well of capture, so that the aspiration of biogas does not cause unintended oxygenation and reduces landfill biogas production by aerobic conditions.

Each wellhead located on the surface of the landfill must be sealed as airtight as possible. The sealing of the wellhead can be ensured by the compaction of clay covering materials in the vicinity of the chimneys, complemented if necessary, placing a polyethylene film to cover surfaces between 200 and 300 m^2 around each well. This system is used to prevent the entry of air and thus oxygen, to the compacted waste.

- Uptake of gas and its conduction

Each wellhead is connected to pipes of high density polyethylene (HDPE) of 110 or 90 mm in diameter. These pipes in groups, will lead the gas with minimum slopes of 2% to regulation stations.

- Regulation stations

HDPE pipes from wells, form groups according to their closeness. Each set of pipes goes to a collector where the concentration of methane (CH_4) and oxygen (O_2) is continuously measured. Other devices measure the pressure, and a valve regulates the flow.

The collector of each station leads the gas mixture to the extraction plant; it is centralized in a picture-programmable computer control.

- Extraction system

Mixture gas pipes from regulation stations converge at the entrance of the extraction plant in a single intake manifold. The suction gas is sent to the delivery manifold where it is distributed for use (cogeneration or torch).

The amount of gas that is sent to cogeneration (CHP) must contain a minimum of methane in the mixture. Therefore, an automatic valve regulates the gas flow direction, depending on the indication of the methane analyzer.

- Cogeneration

Cogeneration is the alternating electric generation by a group of internal combustion engine-electric generator.

- Torch

This is a safety system which burns the excess of gas cogeneration. It must have sufficient capacity to burn 100% of the captured gas.

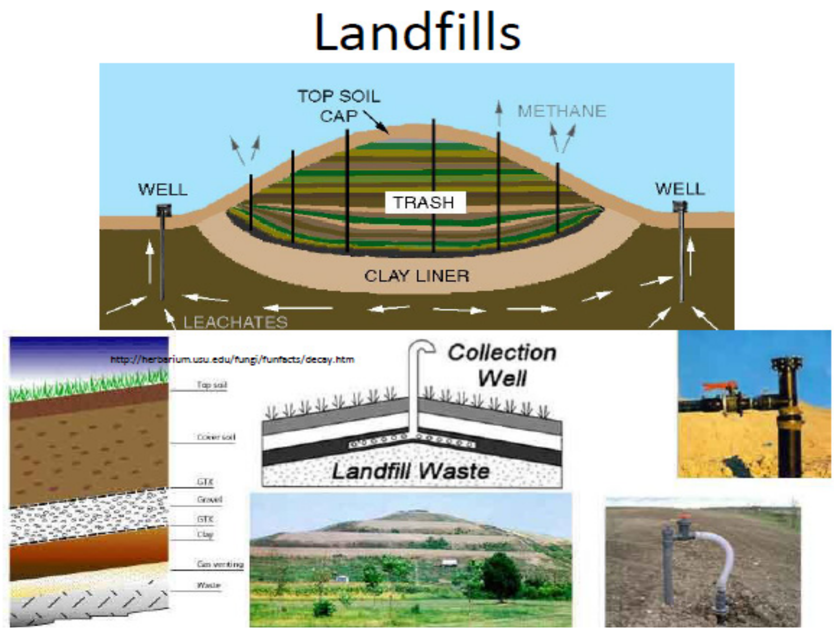
- Gas control

It provides control of gas collection facilities, the analysis, the control of cogeneration based on the quantity and quality of gas produced, and centralization of data in a control center with computer support.

4.3 Minimizing impacts on the atmosphere

- Improving landfill gas recovery and utilization:
  - 10% of the gas recovered is utilized for heat generation (direct use)
  - 40% is used for electricity generation
  - 60% is flared (burned)

- Diverting biodegradable waste from landfill:
  - 50% of the reduction is achieved through paper recycling
  - 15% is achieved using 'lower' cost techniques such as turned windrow Composting
  - 25% is achieved through 'medium cost' techniques such as incineration, and
  - 15% is achieved through higher cost techniques such as anaerobic digestion or more highly engineered composting schemes



Source: http://www.globalenergymanagement.com/Landfill-Gas-Capture.php

4.4 Landfill mining

As available land and resources become increasingly scarce, options to harness these from alternative sources become more sought after. One of the options available is Landfill Mining (LFM). LFM is commonly understood to be the extraction of waste from a landfill site after that site has closed and is no longer accepting waste. With a significant proportion of the world's waste still being disposed of in landfill, there is the potential for significant resources to be recovered post-disposal. In the future old landfills are likely to be considered as exploitable material stocks.

It appears that there are three main strategic reasons for LFM operations: Extraction recycling potential; extraction for energy recovery; and the reclamation of land. Whilst the first two are clear economic arguments about the potential income from the deposited wastes, the third has greater potential for considering environmental and wider sustainability drivers.

4.4.1 Advantages and disadvantages of landfill mining operations

The extraction of wastes for their recycling potential is highly likely to be driven by the material values in the market place for specific recyclates. Metals and plastics are those materials which have the highest values and the lowest level of degradation within a landfill site. These are, therefore, often cited as targets for LFM. However, there may be others that have a specific local value. The benefits to resource security need to be considered.

The reasons covered by the broad term 'land reclamation' may include one or a combination of the following:

- Landfill sites may be in locations that are, was it not for the landfill operations, ideal for traditional development purposes;
- The landfill site may form a physical barrier to a development that is planned, such as the Channel Tunnel Rail Link in the United Kingdom;
- It may be contaminating the groundwater or surrounding area and the source requires removal; or,
- There may be a need to reuse the available landfill space at that site for different kinds of wastes more suitable to long-term disposal, such as non-reactive hazardous wastes (e.g. asbestos).

Materials and energy recovery are likely to be primarily dependent on economic factors, land reclamation may be driven by environmental reasoning. When the widest range of benefits is considered, the greatest benefits can be driven from an LFM operation that can have significant costs and other impacts.

When the widest range of benefits is considered, the greatest benefits can be driven from an LFM operation that can have significant costs and other impacts.

On the other hand, it is only in recent years that accurate knowledge, and then only in broad terms, is available to assess what wastes a landfill site may contain. This lack of knowledge merely increases the risks that would otherwise be present during LFM operations.

The risks of excavation of a landfill site include:

- Nuisance caused during the LFM operation
- Potential for presence of hazardous materials
- Escope of leachate or landfill gas during LFM operations

Many of these risks are similar to traditional mining operations but are enhanced by the heterogeneous nature of the wastes in a landfill. They are also similar to the risks posed by landfilling operations but in reverse. If LFM were not to take place, the waste would remain contained and have limited opportunity to realise the hazards caused.

4.4.2 Technical requirements and considerations

LFM is a combination of processes. These can be broken down into:

1. Preliminary works
2. Extraction of waste
3. Processing of waste
4. End-markets
5. Remediation of land
6. Subsequent development

Following the preliminary works of site preparation, surveys, investigations and programming resources, the physical operation of LFM is a relatively simple one for an experienced landfill or mining operator. However, there are specific risks that need to be considered. The discovery and handling of hazardous materials within the landfill has the potential to hold up, and increase the costs of, LFM operations.

Once the waste is extracted, it needs to be processed according to the objectives of the scheme. This may be for recyclables recovery, where there will be specific standards depending upon material and the end-markets will have their own requirements. These will vary from place to place and may have specific regulatory controls.

Any form of energy recovery is likely to require pre-treatment shredding, trommel screens and metal extraction. It may also require drying to reduce moisture content. There will be significant variability in the composition and consistency of the waste through the different stages of the excavation and the pre-treatment systems need to be able to provide a homogenous output for a waste-to-energy plant to deal with. This may need to be completed on site prior to transportation so that only a stabilised product is being moved and the associated haulage costs and risks reduced.

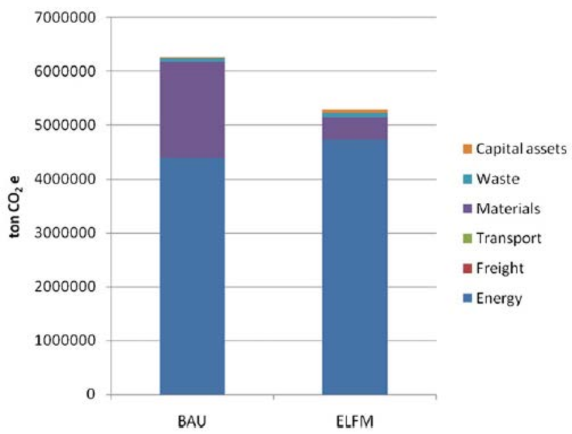
Once the site has been completely excavated, there will be a requirement to remediate the land to remove any residual pollution if the intention is to develop the site for an alternative purpose or to remove the future burden. This will be a specific operation that will require intensive ground investigations and analysis of the groundwater and soils in the area. By removing the source, this part of the process becomes one of containment and decontamination. It is likely that this would be possible using traditional land remediation techniques.

The subsequent development of a landfill may be specified as part of the objectives of the scheme. Depending on the extent of the remediation, it is likely that a specialist operator would not be required at this stage and a construction contractor experienced in brownfield development may be sufficient.

4.4.3 Costs and benefits to society

According to a study conducted by Van Passel, S., et al. (2012), show that Enhanced Landfill Mining (ELFM) projects have a clear private economic potential when adequate regulation and support policies are in place. This is important because it shows that there is scope for private entrepreneurs to invest profitably in ELFM projects. In this section we broaden the scope of analysis by including also some of the most significant external effects of ELFM projects for the society. In particular, we want to explore the environmental impact of ELFM projects. In a first step we focus on the carbon footprint of the "Closing the Circle" case study. The footprint will be assessed and later monetized. In a second step the analysis of impacts for society is extended to the valuation of other benefits to society.

Van Passel, S., et al. (2012) performed the carbon footprint analysis for two scenarios assuming a time frame of 20 years. In this way, they investigated which scenario is the most beneficial in terms of climate change mitigation. The Remo site (Flanders, Belgium) is an existing landfill containing historical waste with energy recovery from methane. The energy recovery from methane would last for about 15 years, using a combined heat and power (CHP) cycle. This will generate an amount of electricity and an amount of recoverable heat. Keeping the situation unchanged 'forever' is called the Business as usual (BAU) scenario. No incoming materials, no outgoing materials. In a second scenario (ELFM) most of the historical waste from the Remo site would be recovered as energy and materials. As in the BAU scenario, energy recovered from methane would last for about 15 years. In the ELFM scenario, however, a waste-to-energy (WtE) plant and a sorting and recycling plant (WtM) need to be built on the Remo site. All operational emissions of the six categories mentioned are taken into account (see the next figure). It was assumed that biogenic emissions do not generate any net addition to global warming.



Carbon footprint of BAU and ELFM scenario.

Source: Van Passel, S., et al., The economics of enhanced landfill mining: private and societal performance drivers, Journal of Cleaner Production (2012), doi:10.1016/j.jclepro.2012.03.024

The BAU scenario would only produce a small amount of energy (from methane recovery), and not producing any materials. Therefore, the difference in materials and energy will be purchased on the market in the case of the BAU scenario. Greenhouse gas emissions of conventional market production methods will be accounted for in the BAU carbon footprint. Comparing the footprints of both scenarios; gives us an idea of which scenario is more beneficial towards greenhouse gas mitigation.

The summarized output data in the next table show that, under current conditions, WtE constitutes the most important cost (about 60% of all costs) as well as the most important benefit (more than 70% of all benefits). The development of innovative technologies (and especially Waste-to-Energy technologies) is an important aspect to improve the feasibility of ELFM practices. Logically, market prices also have an impact on the economic performance of ELFM.

Cost-benefit simulation tool: illustration for ELFM in Flanders.

General data	
Surface (m^2)	20,000,000
Excavated volume (m^3)	160,000,000
Weight cover soil (ton)	26,000,000
Weight waste (ton)	182,000,000
Treatment data	
WtM fraction: cover soil, granulates, metals (ton)	62,400,000
WtE fraction before drying (ton)	100,100,000
WtE electricity production (MWh)	97,493,229
Fines (ton)	45,500,000
Present value Costs	
Excavation (€)	177,894,199
Sorting & pre-treatment (€)	2,698,062 017
Incineration (€)	6,304,862 647
Contingency (€)	918,081,886
Present value Revenues	
WtM (€)	2,637,355 621
WtE (€)	8,785,195 215
Land reclamation (€)	800,000,000
Total (€)	2,123,650 088

Source: Van Passel, S., et al., The economics of enhanced landfill mining: private and societal performance drivers, Journal of Cleaner Production (2012), doi:10.1016/j.jclepro.2012.03.024

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Chapter

4

Water Management and Planning

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Chapter 4

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ABSTRACT

Water is life, sustaining ecosystems and regulating our climate. But it's a finite resource, and less than 1% of the world's fresh water is accesible for direct human use. The field of water resources covers a wide range of topics and subject matter. It is well recognised that water planners require a broad set of inter-disciplinary skills to engage effectively with the multi-faceted, complex nature of contemporary water management challenges. Solving water-related problems, requires scientific expertise and skills for engaging with communities and the ability to integrate environmental, social and political considerations into planning practice. The 21st century will be an era of increased global concern regarding the availability of water.

Besides, climate change has become a hot topic both for the scientific community and the population in general. Despite the climate pattern has been changing continuously during the Earth´s history due to changes in the atmosphere, topography, volcanic activity, and other natural factors, this change seems to have been exacerbated recently due to the alteration of the greenhouse gases content in the atmosphere by the humanity. Nowadays, the extent of this change and its effects on the environment have got relevance due to its influence on disaster risks and its effects on properties and population. It is easy to understand why the water cycle is one of the most environmental drivers affected by climate change. Global warming, leaded last century by the climate change, has involved alterations in the temperature, precipitation and evaporation patters. From the point of view of

the water resources, these changes include an increase in the freshwater losses from terrestrial sources (glaciers, ice and snow, lakes, soil moisture, swamps, groundwater, marches and rivers) by evaporation and sublimation from fresh water deposits and transpiration from the vegetation, but also changes in the rainfall quantity and patterns. As a result, climate change has leaded short and long-term alterations in the frequency of extreme water-related events such as floods of droughts which directly impact on, among others, the quantity but also quality of water resources.

This module focuses on one of those, the issue of water supply planning and resource management, in particular, the planning process, systems analysis methods; institutional framework for water resources engineering; comprehensive integration of engineering, economic, environmental, security, legal, and political considerations in water resources development and management. It further discusses the environmental, economic, and social implications of floods, droughts, dams, and water usage as well as current issues in water quality, water pollution, and water resource regulation.

The overall aim of the module is to develop the skills of the students to know how to plan, develop and manage water resources.

1 WATER PLANNING

1.1 Introduction

Water is an increasingly critical issue at the forefront of global policy change, management and planning. There are growing concerns about water as a renewable resource, its availability for a wide range of users, aquatic ecosystem health, and global issues relating to climate change, water security and water trading.

Water Resources Management Plans should ensure an efficient, sustainable use of water resources. They should focus on delivering efficiently the outcomes that customers want, while reflecting the value that society places on the environment, also considers how water resources can become more integrated and sustainable.

1.2 Water plans

Water plans must include recommended alternatives for regional water resources management, water conservation, protection of the regional public welfare, and time lines for implementing the water plan. The primary factor that was taken into consideration was rainfall which is an important influence on the availability of water resources, such as boreholes, rivers or springs.

The water budget begins with the amount of water provided by precipitation as the total available water in the watershed.The plan will be reviewed and updated every five years. This will allow incorporating any refinements in climate change and population forecasts into the forecasts.

Figure 1: Lake in Azores Island, San Miguel (Santamarta-Cerezal, 2013).

According to Loucks and van Beek (2005), planning and management activities should pay attention to these possible negative consequences of industrial development, population growth and the intensive use of pesticides and fertilizers in urban as well as in agricultural areas. Issues regarding the environment and water quality include:

- Upstream versus downstream conflicts on meeting water quality standards
- Threats from aquatic nuisance species
- Threats from the chemical, physical and biological water quality of the watershed's aquatic resources
- Quality standards for recycled water
- Non-point source pollution discharges, including sediment from erosion
- Inadequate groundwater protection compacts and concerned institutions

1.3 Water plans objectives and strategies

The water plans objetives include;

To introduce a Water Act as well as revise existing laws and regulations to serve as principal legislation for efficient management of national water resources.

To establish a national level organization responsible for policy formulation; oversee implementation of the policy by concerned agencies; and establish basin-level and local level organizations with supporting laws.

Appropriate water allocation for all user sectors at the national and basin levels:

- Define rights and responsibility of the various user sectors
- Prioritize water use for the various sectors, i.e., agriculture, domestic, industry, conservation of ecosystem etc
- Promote conjunctive use of surface and groundwater
- Set water-use criteria/proportions for the various sectors from national to basin level
- Prepare emergency plans (drought, flood and wastewater)

Improvement of water-use efficiency:

- Apply economic and financial tools for water allocation, fee collection, the creation of a water market, compensation, taxes and allow users to be responsible for paying for service, wastewater treatment etc

- Campaign to create awareness of users about the necessity to share costs and use water efficiently
- Set up a water resources management fund
- Introduce water reuse/recycling
- Introduce water saving technologies

To increase water management efficiency:

- Rehabilitate existing infrastructures
- Develop a water network/grid both within and among basins, and a distribution system to serve as many users as possible
- Improve the organizational structure and management system

To develop water resources in accordance with potential and needs of various activities, both in terms of quantity and quality with due consideration of the environment. To ensur sufficient and equitable water for the various basic needs:

- Set clear direction for water resources development both within and outside the country by emphasizing development of water resources within the country to their full potential

To create awareness of the importance of water resources and efficient utilization:

- Include water related topic at all levels of educational curriculum
- Promote public awareness and understanding of the importance and maintenance of water sources and efficient utilization

To have a clear flood, drought and water quality protection plan and introduce an efficient flood and drought protection system:

- Formulate flood and draught protection and rehabilitation master plans, employing bothstructural and non-structural measures
- Promote and support local organizations to be capable of reduce and solve flood anddrought problem
- Develop a preparatory process for protection and rehabilitation operations prior, during and

- after disasters
- Set up a forecasting and warning system
- Set guidelines and procedure for water related disaster warning

1.4 Water budget

Water covers 70% of the earth's surface, but it is difficult to comprehend the total amount of water when we only see a small portion of it. The oceans contain 97.5% of the earth's water, land 2.4%, and the atmosphere holds less than 0.001%, which may seem surprising because water plays such an important role in weather. The annual precipitation for the earth is more than 30 times the atmosphere's total capacity to hold water. This fact indicates the rapid recycling of water that must occur between the earth's surface and the atmosphere.

Knowledge of the water balance is needed to define the lack and excess water and it applies to the climatic classifications, defining an island hydrology and water planning. A water balance analyzes the input and output of water in an area of a watershed over time, taking into consideration changes in the internal storage under different scenarios, such as the effects of climate change.

The importance of water balance is that it is a study that helps us define deficit or surplus water in a watershed taking parameters like rainfall, relative humidity, temperature, evaporation, evapotranspiration and the main flow of the drainage network of the watershed.

The continuity equation is based on the difference that occurs between the inputs and outputs of water mean water that is stored.

$$\text{Inputs - Outputs = Change in Storage}$$

Applying these concepts, precipitation is expressed as:

$$P = E + R + I + e$$

Being e the error in the estimates or closing error, E evapotranspiration, R runoff and I infiltration.

The usefulness of the knowledge of the water balance is that it allows us to perform a hydrological planning in accordance with the data coming out in the survey results, essential for integrated water management in the islands.

In relation to the water balance of the islands, especially oceanic the following singularities must be taken into account (Santamarta, 2013).

- High demand for water resources for agriculture
- Overpopulation
- Scarce water resources in general
- Significant seasonal tourism
- Isolated systems
- Binomial water-energy

Figure 2: Rain over forest in Hierro Island, Canary Archipielago (Santamarta-Cerezal, 2013).

Natural watershed systems maintain a balance between precipitation, runoff to lakes, rivers and wetlands, etc., infiltration to the groundwater system, and water which either evaporates (from open water surfaces) or transpirates from vegetation (evapotranspiration), completing the natural cycle back into atmospheric moisture and precipitation. It is necessary to understand this balance or water budget in order to sustain the resource and its environmental and human connections in the watershed. The understanding of the hydrologic cycle on a watershed basis is essential for development and implementation of appropriate watershed management policies and procedures.

A water budget analysis is a computational technique that balances water input and output while accounting for change in storage. On a watershed scale knowledge of these relationships can be used in addressing major decisions relating to such issues as:

- Land use and watershed planning
- Ensuring sustainable development
- Determining the receiving stream capacity for waste discharge
- Assessing risk exposure;
- Evaluating economic benefit to the community
- Reporting environmental conditions and status.

1.5 Water planning and climate change

The most important impacts of Climate Change will be on the Earth's water cycle. Understanding the water cycle and how it will be modified by climate change is a real challenge. The water cycle describes the constant movement of water from ocean to atmosphere to the land surface and back to the ocean. On a global scale the total amount of water does not change but where it is distributed does.

Water scarcity is expected to become an ever-increasing problem in the future, for various reasons. First, the distribution of precipitation in space and time is very uneven, leading to tremendous temporal variability in water resources worldwide (Oki et al, 2006).

Second, the rate of evaporation varies a great deal, depending on temperature and relative humidity, which impacts the amount of water available to replenish groundwater supplies. The combination of shorter duration but more intense rainfall (meaning more runoff and less infiltration) combined with increased evapotranspiration (the sum of evaporation and plant transpiration from the earth's land surface to atmosphere) and increased irrigation is expected to lead to groundwater depletion (Konikow and Kendy 2005).

As climate change warms the atmosphere and alters the hydrological cycle, we will continue to witness changes to the amount, timing, form, and intensity of precipitation and the flow of water in watersheds, as well as the quality of aquatic and marine environments, Already, water-related climate change impacts are being experienced in the form of more severe and more frequent droughts and floods. Higher average temperatures and changes in precipitation and temperature extremes are projected to affect the availability of water resources through changes in rainfall distribution, soil moisture, glacier and ice/snow melt, and river and groundwater flows; these factors are expected to lead to further deterioration of water quality as well.

The premises that water planning is best done on a regional level is due to the many variables in climate, water supply, water demand, and legal and institutional constraints to water resources management.

1.6 Water management on islands

Water problems on islands are mainly related to the limited water resources. Due to the limited water resources, water related problems that are common elsewhere as well, such as pollution by wastewater and inadequate water supply systems (mainly huge leakages) become more acute on islands and thus require special attention and appropriate management (Hophmayer, 2012).

Islands depend, as other mainland countries, upon the quality and quantity of their water for their existence and economic activities. However, water management on islands is unique as it is constrained by their size, isolation from the mainland, fragility, and limited human, natural and financial resources (Pacific Islands Forum, 2005).

Small islands frequently have a relatively limited capacity to store water for use in the dry season, and the construction of large reservoirs is often prohibited by the requirement to flood scarce land. In addition, torrential rains, coupled with steep topography, short river channels and easily eroded soils, can cause siltation of reservoirs, further decreasing storage capacity (Khaka, 1998).

Figure 3: Landscale in Hawaii islands (Santamarta-Cerezal, 2013).

1.7 Useful links

- WATER - Environment - European Commission
- Climate Change and Water - US Environmental Protection Agency
- Water resources systems planning and management
- Ground Water Development, Sustaninability, and Water Budgets
- Climate Uncertainty: What it Means for Water Planning and Policy
- Water Resource Planning Options for Climate Change

2 WATER USES

2.1 Introduction

An adequate supply of water is essential to ensure continued economic vitality and quality of life. Water use must generally respond to two needs: the need to satisfy the growing demand for water used for human consumption and for production processes (industry, agriculture, recreation), and the need to preserve water quality and protect the environment. This requires the identification, characterization, management and protection of water resources.

The most important water uses are;

- For drinking purpose
- For washing, bathing and cooking etc
- For building construction
- For the generation of steam for industrial use and electricity generation
- For generating hydroelectricity
- As a solvent
- For irrigation purposes

Water is crucial for the economy. Virtually every industry from agriculture, electric power and industrial manufacturing to beverage, apparel, and tourism relies on it to grow and ultimately sustain their business. Generally, the largest percentage of water consumption is attributed to agriculture.

Accounting for water is an essential step toward ensuring that a water utility is sustainable. This is best accomplished when water systems meter use by their customers. Metering helps to identify losses due to leakage and also provides the foundation on which to build an equitable rate structure to ensure adequate revenue to operate the system.

Options for water demand reduction:

- More efficient fixtures for new developments

- Landscaping and storm water management
- Grey water use
- Revised irrigation strategies and technologies
- Water pricing
- Education
- Incentives
- Retrofitting

Two-thirds of the world's population is projected to face water scarcity by 2025, according to United Nations (2006). Factors Affecting Population Trends:

- Birth rate
- Death rate
- Immigration
- Emigration
- Government policies
- Religious and societal beliefs
- Catastrophes
- State of the Economy

2.2 Water footprint

The water-footprint concept was coined in 2002 by Arjen Hoekstra, a professor of water management at University of Twente in the Netherlands. Using data from the UN's Food and Agricultural Organization, Mr. Hoekstra and other researchers gauged the water content that went into the making of various products and applied those statistics to people's consumption patterns to get a rough water footprint for average individuals and nations as a whole.

People use lots of water for drinking, cooking and washing, but even more for producing things such as food, paper, cotton clothes, etc. The water footprint is an indicator of water use that looks at both direct and indirect water use of a consumer or producer. The water footprint of an individual, community or business is defined as the total volume of freshwater that is used to produce the goods and services consumed by the individual or community or produced by the business.

2.3 Agricultura water uses

Water constitutes a key component in food production. Agricultural use of water accounts for nearly 70% of the water used throughout the world, and the majority of this water is used for irrigation. On the negative side, irrigation of land causes salinization of the land that is being irrigated, mostly in arid and semi-arid regions. Irrigation of cropland can increase the possibility fertilizers and pesticides will infiltrate into the groundwater or runoff into nearby streams. Along with the irrigation of crops, the farmers that have livestock must provide clean water for the livestock to drink.

Figure 4: Pineapple crops in Hawaii Islands (Santamarta-Cerezal, 2013).

2.4 Industrial uses

It is estimated that 15% of worldwide water use is industrial. Major industrial users include power plants, which use water for cooling or as a power source (i.e. hydroelectric plants), ore and oil refineries, which use water in chemical processes, and manufacturing plants, which use water as a solvent.

Some power plants use cooling systems that draw water from a lake, river, aquifer, or ocean to cool steam and then return virtually all of it, although at higher temperatures, to the source. Such systems, known as once-through cooling systems, have high withdrawals but low consumption.

Reusing and recycling industrial water can ease the pressure on water resources and avoid the need to discharge to the sewer and/or environment. With appropriate management, which may include treatment, industrial water can be used for a wide range of purposes including industrial uses (e.g. cooling or material washing) or non-industrial uses (e.g. irrigation or toilet flushing).

2.5 Useful links

- What’s your water footprint?
- The EU’s Water Footprint - Institute for Environment and Sustainability
- Water resources across Europe - European Environment Agency
- TEDxOslo - Angela Morelli - The Global Water Footprint of Humanity
- Water Footprint and Conservation projec

3 SURFACE WATER EXPLOTATION

3.1 Precipitation

The part of the hydrologic cycle that is of most relevance to water planning is the precipitation;

- Some precipitation that falls on land seeps (infiltrates) into the ground to become soil moisture, part of which is taken up by plant roots and returned to the atmosphere through the process of transpiration
- Precipitation that is not intercepted or infiltrated flows across the land surface and through channels, from which it may be diverted for various consumptive uses or used to fill reservoirs, where it is stored until used or evaporated
- When soil moisture storage capacity is exceeded, recharge to groundwater occurs

When rainfall falls on the land surface, typically, depending on the intensity of the rainfall and the permeability and wetness of the soils, some of the rainfall infiltrates into the ground, and the remainder becomes runoff and flows overland to reach the nearest stream channel, thus contributing to river flow or streamflow.

The factors which control runoff generation are rainfall intensity and the permeability of the soil. Since both soil properties and rainfall intensity can vary significantly in space, it is easily possible that runoff generation does not occur uniformly across the catchment.

Surface water budget analyses rely heavily on estimates of components instead of actual measurements. Although precipitation and streamflow are measurable water sources, they are typically measured at only a few locations. Evaporation, evapotranspiration by plants, infiltration, return flows, and spring and seep discharges are generally not measured directly and are therefore estimated. Consequently, the surface water budget calculations presented here have a high degree of uncertainty and should be used with caution.

Figure 5: Surface water catchment (Santamarta-Cerezal, 2013)

3.2 Reservoir related issues

The river yields in semi-arid zones show major fluctuations, both on a seasonal and annual basis. Dam building, or other hydraulic works, is the way usually to control water quantity, as far as meeting demands is concerned.

Reservoir is a natural or artificial lake, storage pond or impoundment from a dam which is used to store water. Reservoirs may be created in river valleys by the construction of a dam or may be built by excavation in the ground or by conventional construction techniques such as brickwork or cast concrete.

The ecological quality of rivers must be maintained by maintaining a minimum flow. Rivers must not dry-up or have their physical regimes significantly altered in order to conserve the hydrological and ecological functions of their drainage networks.

Degradation of the riverbed upstream of reservoirs may increase the risks of flooding in those areas. Reservoir construction inevitably results in loss of land and forces the evacuation of residents due to impoundment

Water stored here during wet times is used during dry times, making the region's water supply more drought resistant, reliable and flexible.

The reasons for constructing reservoirs are ancient in origin, and initially focused on the need of humans to protect themselves during periods of drought or floods. Accordingly, reservoirs are usually found in areas of water scarcity, or where a controlled water facility was necessary.

3.2.1 Dams

A dam is any barrier that holds back water; dams are primarily used to save, manage, and/or prevent the flow of excess water into specific regions. In addition, some dams are used to generate hydropower. There are several different kinds of dams. Some dams are called embankment dams. Embankment dams are called either earthfill dams or rockfill dams, depending on what material is used most in the dam. Earthfill dams are made mostly of soil, or earth. Rockfill dams are made mostly of rocks. Other dams are made of concrete. Concrete dams can be either gravity dams or concrete arch dams, depending on how they are built.

Dams and reservoirs serve a number of different functions but one of the largest is to maintain an area's water supply. Many of the world's largest urban areas are supplied with water from rivers that are blocked via dams. Another major use of dams is power generation as hydroelectric power is one of the world's major sources of electricity. Hydropower is generated when the potential energy of the water on the dam drives a water turbine which in then turns a generator and creates electricity. To best make use of the water's power, a common type of hydroelectric dam uses reservoirs with different levels to adjust the amount of energy generated as it is needed. When demand is low for instance, water is held in an upper reservoir and as demand increases, the water is released into a lower reservoir where it spins a turbine. Some other important uses of dams and reservoirs include a stabilization of water flow and irrigation, flood prevention, water diversion and recreation.

3.2.2 Water storage ponds

The demand for water has increased tremendously in recent years, and ponds are one of the most reliable and economical sources of water. Ponds are now serving a variety of purposes, including water for livestock and for irrigation, fish production, field and orchard spraying, fire protection, energy conservation, wildlife habitat, recreation, and landscape improvement.

Water storege ponds are a key component in the treatment, storage and distribution of potable water. Built in many sizes and shapes they serve as repositories for the regions water.

Figure 6: Water reservoir (Santamarta-Cerezal, 2013)

3.2.3 Water supply and transport

The functions of the formal urban water supply and wastewater sector include storage, supply, distribution, and wastewater treatment and disposal systems that provide organized water services to established urban areas. The infrastructure generally includes water and wastewater utility systems with large raw-water storage facilities, storm-water collection systems, trans-basin diversion structures, potable and wastewater treatment plant equipment, pipelines, local distribution systems, and finished-water storage facilities.

Some urban distribution systems also include secondary distribution systems for reuse of treated wastewater, advanced treatment systems such as reverse osmosis or filtration, and multiple types of storage systems. Treated wastewaters may be distributed to meet irrigation and other non-potable needs, and with adequate treatment can be used to augment some drinking water supplies provided that communities are willing (Hurliman, 2007).

Figure 7: Water channel in Canary Islands (Santamarta-Cerezal, 2013)

Water leaking from water company pipes is wasteful of water and energy if the benefits of reducing it would outweigh the costs.

3.3 Managed aquifer rechargue

Potential sources of recharge water include, but are not limited to, treated wastewater, urban stormwater or groundwater drawn from other aquifers. Some level of pre-treatment of the source water will generally be required prior to recharging the aquifer, depending on the outcome of environmental and health risk assessments.

In urban areas where there's not enough surface water storage, aquifers can provide a way to store excess water when it becomes available until the time it is needed.

Intentionally injecting or depositing water into an aquifer and then extracting the water for use at a later date is known as managed aquifer recharge. There has been an increasing interest in using managed aquifer recharge as a mechanism to store and later supply an alternative water source for various uses. For example, stormwater could be injected into an aquifer and then later reused for watering parks and gardens in drier seasons.

3.4 Useful links

- Water exploitation index - European Union Open Data Portal - Europa
- Water exploitation-FAO
- Rainwater harvesting

4 WATER WASTE, DESALINATION AND REUSE

4.1 Introduction

The European Union's Water Framework Directive (WFD) requires member states to systematically develop River Basin Management Plans (RBMP) with measures to achieve good chemical and biological water quality. In the eyes of strengthening regulatory constraints and of the environmental issues at stake, local government entities must deal with the adaptation of their infrastructures and important decision-making in the fields of drinking water and water sanitation.

The discharges of wastewater by industry and households can have considerable detrimental effects on water quality and, hence, often on public and ecosystem health.

Declining water quality is an acute problem around the world, particularly in developing countries where there are notable increases in agricultural and industrial production, coupled with a lack of adequate wastewater treatment.

Through the natural water cycle, the earth has recycled and reused water for millions of years. Water recycling, though, generally refers to projects that use technology to speed up these natural processes.

Reusing and recycling alternative water supplies is a key part of reducing the pressure on our water resources and the environment. Helping us adapt to climate change and population growth. When considering alternative water supplies, you should choose the most appropriate water source, taking into account end use, risk, resource and energy requirements.

The types of water pollutans are:

- Organic wastes: degradable wastes, residuals, some chemicals (detergents, pesticides, oil)
- Inorganic substances: toxic metals, salts, acids, nitrate and phosphorous compounds
- Nonmaterial pollutants: heat, radioactivity
- Infectious agents: bacteria, viruses

It is important that we all reduce the amount of water we use and manage our use of water more effectively. Drinking water system owners and operators can pursue best industry practices for water efficiency, such as:

- System-wide water loss accounting
- Leak detection and repair
- Pricing that encourages consumer water conservation

Figure 8: pretreatment of waste water (Santamarta-Cerezal, 2013)

4.2 Greywater

Greywater is untreated wastewater that has not been contaminated by any toilet discharge, has not been affected by unhealthy bodily wastes, and does not present a threat from contamination by unhealthful processing, manufacturing, or operating wastes. Greywater can be a good water resource during times of drought and water restrictions, but its reuse can carry health and environmental risks. Under this definition, toilet wastewater (also known as blackwater) is not considered greywater and would require significant treatment in centralized wastewater plants. The importance of greywater recycling and reuse has been recognized recently by many countries.

Greywater is typically wastewater low in turbidity, clear in color, and found from the drainage of bathtubs, showers, bathroom washbasins, clothes washing machines, and laundry tubs. Greywater quality is highly variable because it is source dependent given the variability in household water use.

Heavy greywater and blackwater must be conveyed to and treated by centralized wastewater treatment plants. Only light greywater can be treated on-site for non-potable usage.

4.3 Desalination of water

Due to the growth of the desalination field to help supply water to an exploding active thirsty population, there has been a surge in the number of scientists and engineers involved in water desalting and wastewater reclamation.

Desalination is the process of removing soluble salts from water to render it suitable for drinking, irrigation, or industrial uses. The principal methods used for desalination include distillation (or evaporation), electrodialysis, freezing, ion exchange, and reverse osmosis.

Distillation plants having high capacities and using combustible fuels employ various devices to conserve heat. In the most common system a vacuum is applied to reduce the boiling point of the water, or a spray or thin film of water is exposed to high heat, causing flash evaporation; the water is flashed repeatedly, yielding fresh distilled water.

Figure 9: Desalination Plant (OI) (Santamarta-Cerezal, 2013)

Another method of desalination is by electrodialysis. When salt dissolves in water, it splits up into charged particles called ions. Placed in a container with a negative electrode at one end and a positive electrode at the other, the ions are filtered by the membranes as they are attracted toward the electrodes; they become trapped between semipermeable membranes, leaving outside the membranes a supply of desalinated water that can be tapped.

By far the most promising approach is the reverse osmosis process, in which pressure is applied to saltwater to force it through a special membrane. Only pure water passes, leaving concentrated seawater behind.

4.4 Water waste reclamation

Water reuse allows communities to become less dependent on groundwater and surface water sources and can decrease the diversion of water from sensitive ecosystems. Additionally, water reuse may reduce the nutrient loads from wastewater discharges into waterways, thereby reducing and preventing pollution.The term water recycling is generally used synonymously with water reclamation and water reuse.

Recycled water can be used in numerous applications to satisfy most water demands, depending on the level of treatment. The water is treated to meet regulatory guidelines for the intended end use. Typical uses for recycled water include:

- Surface irrigation
- Groundwater recharge
- Wetlands, wildlife hábitat
- Industrial cooling processes
- Landscape and golf course irrigation
- Toilet flushing and Vehicle washing
- Food crop irrigation
- Potable reuse (typically recharge of groundwater or surface water to augment drinking water supplies)

4.5 Water waste and climate change

There is a need for further research into an environmental accounting system for comparing the climate change impacts of waste management options.Waste is a clear indicator of how much of our natural resources we're using. The cheaper and more abundant our resources, the more we use them and the more we feel we can afford to waste. Not only is climate change a clear symptom of our over-consumption, it is also a result of our extreme levels of resource use. Waste discharge and wastewater treatment are sources of greenhouse gas emissions. Although carbon dioxide (CO_2) and methane (CH_4) have been the main focus in climate change calculations and discussions, the potential impact of nitrous oxide (N_2O), which is also generated from wastewater treatment plants, is now gaining increased prominence.

Professionals working in waste management and associated areas need to ensure that they are aware of current thinking on climate change and the impact of their area of work on greenhouse gas emissions.

Climate change will likely:

- Contaminate coastal surface and groundwater resources due to sea level rise, resulting in saltwater intrusion into rivers, deltas, and aquifers
- Increase water temperatures, leading to more algal and bacterial blooms that further contaminate water supplies
- Increase extreme precipitation and flooding, which will increase erosion rates and wash soil-based pollutants and toxins into waterways
- Contribute to environmental health risks associated with water. For instance, changes in precipitation patterns are likely to increase flooding, and as a result mobilize more pathogens and contaminants

One of the most significant sources of water degradation results from an increase in water temperature. The increase in water temperatures can lead to a bloom in microbial populations, which can have a negative impact on human health. Additionally, the rise in water temperature can adversely affect different inhabitants of the ecosystem due to a species' sensitivity to temperature. The health of a body of water, such as a river, is dependent upon its ability to effectively self-purify through biodegradation, which is hindered when there is a reduced amount of dissolved oxygen. This occur when water warms and its ability to hold oxygen decreases.

Water and wastewater utilities could reduce energy use by just 10 percent through demand management strategies and cost-effective investments in energy efficiency, collectively.

4.6 Useful links

- Urban Waste Water Directive Overview - European Commission
- Desalination: Solving water problems or creating a new one
- Wastewater Treatment Plant Tour - "Flush To Finish"
- World Water Day 2012, Reuse
- Wastewater Treament and Water Reuse Basics
- "Drinking from the sea", explore how and why sea water is desalinated
- Desalination Myths and Misconceptions

5 WATER EFFICIENCY AND SUSTAINABILITY

5.1 Introduction

Conservation of water resources is becoming very important due to climate change concerns, pervasive droughts, and high energy prices. Citing Webber (2008) "Water is needed to generate energy, and energy is needed to deliver water. Thereby both resources are limiting the other". In this context, nowadays, there is an increasing interest in finding ways for using less water and energy while ensuring product or service performance.

While efficiency basically means doing more with less, sustainability refers to meeting the needs of the present generation without compromising the ability of future generations to meet their needs. This however, is a general definition that does not address the presence of environmental quality in sustainability.

A more appropriate definition of sustainability, should account for environmental quality as well as its relationship with the other components of sustainability. Thereby, sustainability means the balance between manipulating the environment for meeting as many human needs as possible and preserving the natural processes of the environment.

5.2 Water efficiency

Water efficiency may be accomplished by using technologies and practices that deliver equal or better service with less water. Water efficiency increases the sustainability of water supplies. By improving water efficiency, operating costs and the need for developing new supplies and for expanding the water infrastructure are reduced. It also diminishes withdrawals from limited freshwater supplies. As a result, there is more water available for future use, and the ambient water quality and aquatic habitat improve (i.e. sustainability is achieved).

Using water more efficiently helps maintaining supplies at safe levels, protecting human health and the environment. When reservoir water levels get lower and ground water tables drop, water supplies, human health, and the environment are put at serious risk. For example, lower water levels can contribute to higher concentrations of natural and human pollutants. Less water going down the drain means more water available in the lakes, rivers and streams that we use for recreation and wildlife uses to survive.

At global scale, water supplies are under pressure from different human activities and are being affected by climate change. In a marked contrast to domestic and industrial withdrawals, agriculture accounts for 80–90% of the freshwater used by humans, and most of that is consumed in crop production. In many areas, this water use is unsustainable.

Although the amount of water required varies greatly between different agricultural types and climatic region, the supply of some freshwater is an absolute essential for all forms of agriculture. Agricultural activity dominates the use of freshwater and in many places has led to large reductions in river flow, to long and repeated periods of zero flow for several major river systems, with consequent huge changes in estuarine and coastal ecosystems. In addition, large freshwater abstraction resulted in overexploitation of many major regional aquifers. A more efficient water use in agriculture will strongly contribute in the sustainability of this resource.

5.3 Water Sustainability

Water resources sustainability means that development of human activities is compatible with preserving and guarantying adequate living conditions for future generations. It maybe achieved by performing efficient use freshwater for economic and social development while maintaining the resource base and environmental carrying capacity for coming generations.

The resource base concept should be widely interpreted, such that besides the natural resource, it also contains knowledge, infrastructure, technology, durables and human resources. When development converts natural resources into other durable products, this remains part of the overall resource base.

The vast majority of planet's water is groundwater (98.5%) and at the human scale, part of it is virtually unreneweable. In contrast, surface water may be considered a renewable resource, but it represents only 1.5% of all the water. In addition, in many parts of the world, fresh water resources are scarce and to a large extent finite. Since there are many ways to jeopardise the future water availability either by overexploitation by destroying resources for future use, development where water use is not sustainable is ill-planned.

From physical point of view, sustainability water resources means closing the resource cycles and considering the cycles in their integrity (water and nutrient cycles). In agriculture this implies primarily closing or shortening water and nutrient cycles for preventing accumulation or depletion of land and water resources.

Water depletion results in desertification, while its accumulation produced water logging. On the one hand, nutrient depletion leads to loss of fertility, loss of water holding capacity, and in general, reduction of carrying capacity. On the other hand, nutrient accumulation produced eutrophication and pollution. Loss of top-soil results in erosion, land degradation and sedimentation elsewhere.

Physical sustainability has to do with closing the cycles within the human dimension. This implies restoring the dynamic equilibria at the appropriate temporal and spatial scales. The latter is relevant, since at a global scale all cycles close.

From an economic point of view, sustainability is related to the efficiency of the system. If all societal costs and benefits are properly accounted for, and cycles are closed, then economic sustainability implies a reduction of scale by short-cutting the cycles. Efficiency implies that cycles should be kept as short as possible. Examples of short cycles are: water conservation, to make optimum use of rainfall where it falls (and not drain it off and capture it downstream to pump it up again); water recycling at the spot instead of draining it off to a treatment plant after which it is conveyed or pumped back over considerable distances etc.

Increasing the scale through trade in land- and water-intensive commodities facilitates economic sustainability. This is the virtual water concept, which is an important in countries where the carrying capacity of a society is not sufficient to produce land and water intensive products itself. Such concept of virtual water is a tool for an equitable utilisation of water resources. This requires an open and accessible global market and the use of resource-based economic incentives such as resource taxing, as opposed to taxing renewable resources such as labour, which is the general practice today.

The abovementioned cycles closing should be carried out at different spatial scales:

- Rural scale: water conservation, nutrient and soil conservation, prevention of over-drainage and the recycling of nutrients and organic waste.
- Urban scale: recycling of water, nutrients and waste in both, towns and mega-cities.
- River basin scale: soil and water conservation in the upper catchment, prevention of runoff and unnecessary drainage and enhancement of infiltration and recharge, flood retention, pollution control and the wise use of wetlands.
- The global scale: water, nutrient and basic resource cycles are integrated and closed (virtual water concept).

5.4 Water Efficiency Strategies for Sustainability

Efficiently interventions in water systems for sustainable water resources development are manifold and depend on the freshwater demanding activity. For example, leak detection programs can reduce the amount of water, pressure, and energy required to deliver the same amount of water to consumers' taps.

Case studies demonstrate substantial opportunities to improve efficiency through supply-side practices, such as accurate meter reading and leak detection and repair programs, as well as through demand-side strategies, such as conservation-based water rates and public education programs.

Farmers in many countries are subject to legislative restrictions on water use, such that, how to reduce agricultural water use and make water resources more sustainable is an increasingly urgent question. It is a question that requires combined agronomic, physiological, biotechnological/genetic and engineering approaches, which collectively represent 'water saving agriculture'.

5.5 Useful links

- Which Economic Model for a Water-Efficient Europe
- Why Water Efficiency | WaterSense | US EPA

6 WATER RESOURCES AND CLIMATE CHANGE

6.1 Introduction

Climate change has become a hot topic both for the scientific community and the population in general. Despite the climate pattern has been changing continuously during the Earth´s history due to changes in the atmosphere, topography, volcanic activity, and other natural factors, this change seems to have been exacerbated recently due to the alteration of the greenhouse gases content in the atmosphere by the humanity.

Nowadays, the extent of this change and its effects on the environment have got relevance due to its influence on disaster risks and its effects on properties and population. It is easy to understand why the water cycle is one of the most environmental drivers affected by climate change (figure 4.10). Global warming, leaded last century by the climate change, has involved alterations in the temperature, precipitation and evaporation patters. From the point of view of the water resources, these changes include an increase in the freshwater losses from terrestrial sources (glaciers, ice and snow, lakes, soil moisture, swamps, groundwater, marches and rivers) by evaporation and sublimation from fresh water deposits and transpiration from the vegetation, but also changes in the rainfall quantity and patterns. As a result, climate change has leaded short and long-term alterations in the frequency of extreme events such as floods of droughts which directly impact on, among others, the quantity but also quality of water resources.

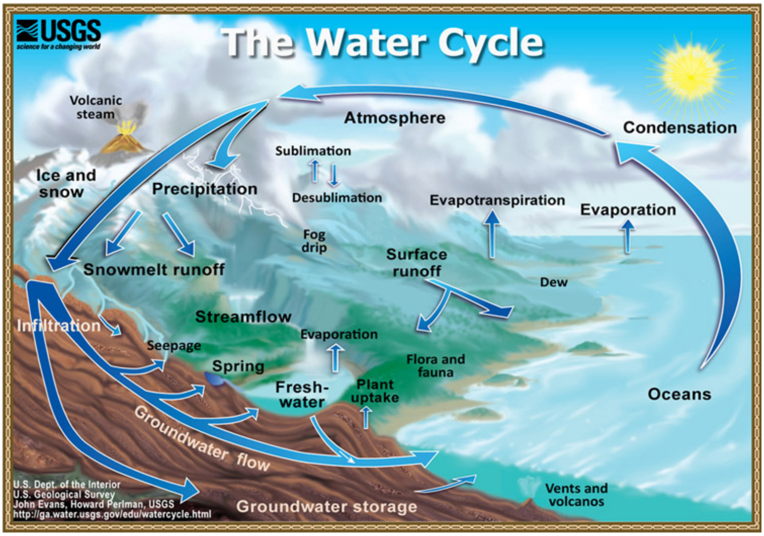

Figure 10: the Water Cycle (U.S. Geological Survey, 2011)

Useful links

- Climate Change 2013 Working Group I: The Physical Science Basis
- BBC THE TRUTH ABOUT CLIMATE CHANGE PART 1

6.2 Modelling climate change

One of the main problems of facing climate change and developing adaptation policies and measures is to evaluate its long-term impacts. Atmospheric and Oceanic Global Circulation Models (AOGCMs) (see e.g. Varis et al., 2004) are nowadays the most useful tools to predict the impact of human activity on the climate change for large spatial and temporal scales. AOGCMs are three-dimensional mathematical models based on basic laws of physics, fluid motion and chemistry which project future climate using the Navier–Stokes equations on a rotating sphere which govern the oceanic and atmospheric interactions (figure 4.11). Some examples are HadCM3 or GFDL CM2.X. The main sources of uncertainty for these models nowadays are:

- Ocean circulation
- Feedback processes
- Termohaline circulation
- Carbon cycle
- Photosynthesis processes
- Clouds and radiation
- Ice and snow albedo

As AOGCMs use a coarse scale (100-200 km grid size resolution) which is not suitable to predict the impact of climate change at regional or local level. As a result, Regional Circulation Models (RCMs) (see e.g. Houghton, 2004) were developed from AOGCMs by regionalizing or "downscaling" their results in order to obtain a finer spatial resolution (Bureau of Meteorology, 2003). Despite the improvement in the results, RCMs still show some extent of inconsistency related to the uncertainty of the AOGCMs they stem from.

From the point of view of the water resources, the impact of climate change depends not only on the climate behaviour but also in the population development. The Intergovernmental Panel on Climate Change (IPCC), through the Special Report on Emission Scenery (SRES) (IPCC, 2000), have developed emission scenarios grouped in six families (table 4.1) which project the future greenhouse gases emissions (figure 4.12) based on the most likely population, politic, social and economic changes.

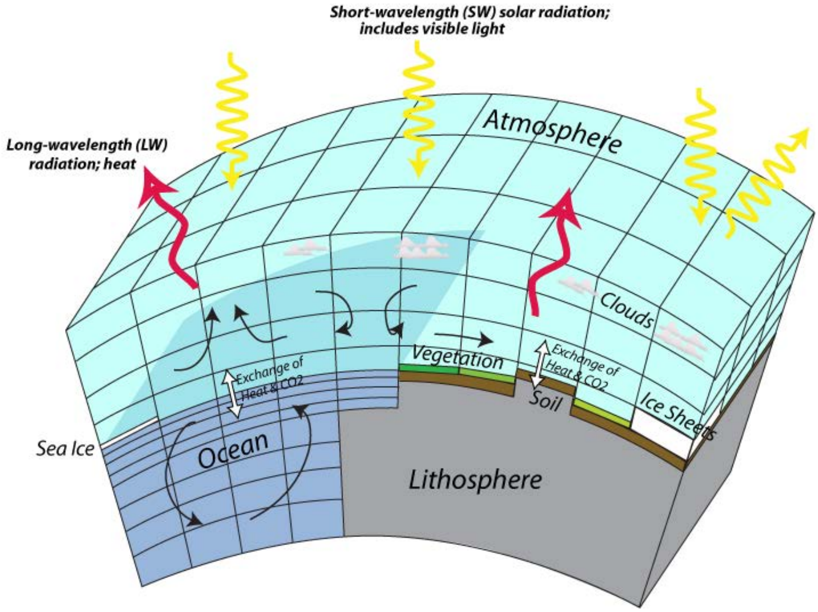

Figure 11: Schematic structure of an Atmospheric and Oceanic General Circulation Model (source: (Bralower and Bice, 2014))

Table 1: Special Report on Emission Scenery scenarios (Source: (IPCC, 2000))

Description		Description
Global market	A1	Very rapid economic growth Low population growth Rapid introduction of new efficient technologies. Convergence among regions in terms of income and way of life
	A1FI	Similar to A1 An emphasis on fossil-fuels
	A1B	Similar to A1 A balanced emphasis on all energy sources
	A1T	Similar to A1 Emphasis on non-fossil energy sources

A2 Regional enterprise	Self-reliance and preservation of local identities Continuous population growth Primarily regionally oriented economic development Economic growth and technological changes are fragmented and slow
B1 Global sustainability	Rapid economic growth as in A1 Rapid changes toward a service and information economy Low population growth as in the A1 storyline Reductions in material intensity and the introduction of clean and resource efficient technologies Global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives
B2 Local Stewardship	Emphasis on local solutions to economic social and environmental sustainability Continue and moderate population growth (less than in A2) Intermediate levels of economic development Less rapid and more fragmented technological change than in the B1 and A1

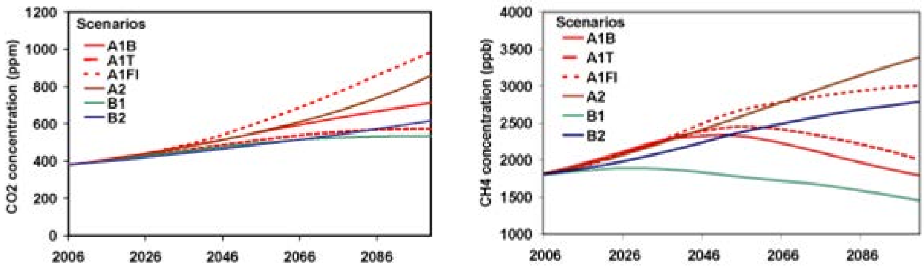

Figure 12: Projected greenhouse gases emission using the scenarios described by IPCC (2006-2100) (source: (U.S. Environmental Protection Agency, 2011))

6.2.1 Useful links

- Wikipedia: General Circulation Models
- What is a GCM? - the IPCC Data Distribution Centre
- The Greenhouse Effect and Climate Change
- IPCC Special Report: Emissions Scenarios (SRES)

6.3 Impacts of climate change

Impacts on water resources by the climate change are temporary and spatially dependent:

- Temporary differences refer to short-term or immediate impacts and long-term or gradual and deeper changes in the hydrological cycle such as spatial and temporal distribution of floods and drought, changes in land uses as a response to the climatic change, etc.
- Spatial differences are related to the diverse response of different regions to the alteration of the climatic patterns.
    - In general (North Hemisphere), it is expected an increase in the quantity of water resources in northern countries as they become wetter.
    - The opposite trend could affect southern countries as their temperature increase considerably affecting evaporation and transpiration processes and their precipitation decrease and become more intense unbalancing hydrological functions such as runoff-rainfall ratio.
    - From the point of view of the quality of the water resources, a substantial decrease in this parameter related to the increase in the water temperature, sediments suspended, nutrients and eutrophication processes could be expected.

- However, particular trends of water resources quantity and quality show a high regional dependence due to the large number of factors involved and impacted by the climate change, and resilience of the different environments to them.

Due to the importance and high degree of uncertainty arising from its impacts, climate change may be the most challenging issue that world must face nowadays (Watkiss et al., 2005) and including adapting measures in the decision-making processes and policies is essential to prevent or mitigate its effects.

6.3.1 Temperature and sea level

Based on the prediction models and SRES scenarios described before, projections of climate change impacts on temperature and sea level could be developed (table 4.2). According to these projections, a temperature rise of about 0.1ºC per decade would be expected and of 0.2 ºC projected for the next two decades for all SRES scenarios. The temperature will rise between 1.8 and 4.0 ºC and the sea level rise will range from 18 to 59 cm depending on the scenario. In general, scenario A1F1 is the most extreme mainly due to its rapid economic growth and the use of fossil fuels, whilst scenario B1 show moderate figures because introduction of clean and resource efficient technologies and the rapid changes toward a service and information economy. Besides, it is very likely that hot extremes, heat waves and heavy precipitation events will continue to become more frequent affecting terrestrial and aquatic ecosystems and physical processes such as ocean circulation, photosynthesis processes, evaporation, etc.

Uncertainty on the predicted impact of climate change on temperature and sea level may arise from both the different AOGCMs used and SRES scenarios. SRES scenarios set different future greenhouse emissions whilst different AOGCMs use their own calculations to obtain projected future values.

On the other hand, the high temporal and regional dependence of the climate change process is highlighted by the fact that the highest increase in both temperature and sea level are projected to be recorded in the North Pole during the last half of the 21st century according to the different SRES scenarios and AOGCMs (figure 4.13). Warming is expected to be greatest over land and at most high northern latitudes and least over Southern Ocean and parts of the North Atlantic Ocean.

Table 2: Projected temperature and sea level rises by 2100 according to the SRES scenarios (Source: (IPCC, 2007))

Scenario	Description
B1	Best estimate temperature rise of 1.8 °C with a likely range of 1.1 to 2.9 °C Sea level rise likely range 18 to 38 cm
A1T	Best estimate temperature rise of 2.4 °C with a likely range of 1.4 to 3.8 °C Sea level rise likely range 20 to 45 cm
B2	Best estimate temperature rise of 2.4 °C with a likely range of 1.4 to 3.8 °C Sea level rise likely range 20 to 43 cm
A1B	Best estimate temperature rise of 2.8 °C with a likely range of 1.7 to 4.4 °C Sea level rise likely range 21 to 48 cm
A2	Best estimate temperature rise of 3.4 °C with a likely range of 2.0 to 5.4 °C Sea level rise likely range 23 to 51 cm
A1FI	Best estimate temperature rise of 4.0 °C with a likely range of 2.4 to 6.4 °C Sea level rise likely range 26 to 59 cm

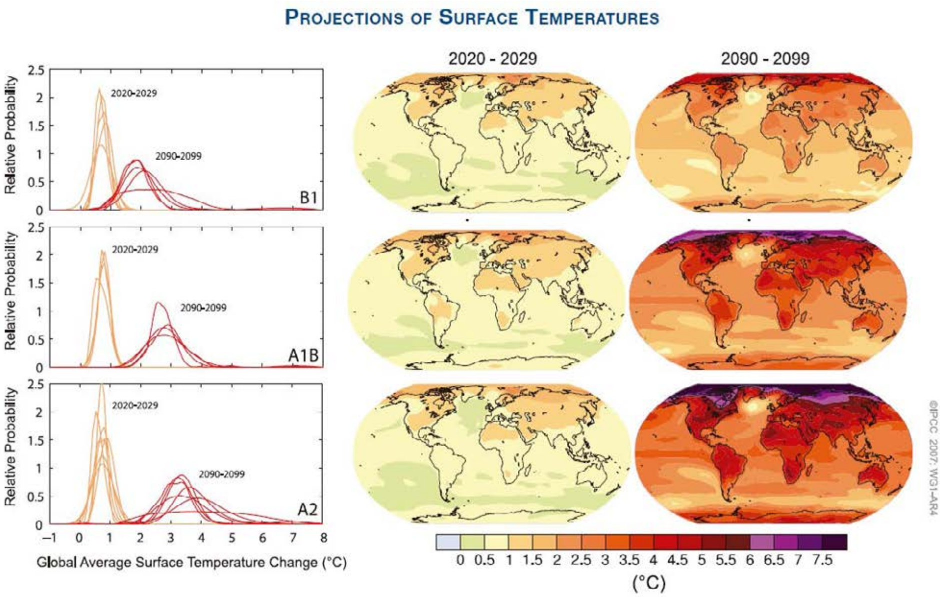

Figure 13: Projected global warming using SRES scenarios for 2020-2099 relative to 1980-1999 (right) and uncertainties for this predictions from different AOGMCs (left) (source: (IPCC, 2007))

6.3.2 Trends in precipitation and evaporation

The effects of the climate change, global warming and associated environmental alterations affect water resources with a temporal and regional dependence. In general, the global warming processes mentioned above will increase evaporation of water from land and water surfaces. Despite on average evaporation is directly related with precipitation, at regional scale precipitation patterns will become even more complex and variable given that the changes in the evaporation depend on many temporary and spatially heterogeneous factors (temperature, humidity, wind patterns, net radiation, available soil moisture, etc.). In general, according to IPCC (2007) it is likely that:

- Tropical cyclones will become more intense, with more heavy precipitation associated with on-going increases of tropical sea surface temperatures
- Extratropical storm tracks are projected to move poleward, with consequent changes in wind, precipitation and temperature patterns
- Sea ice will shrink in both the Arctic and Antarctic under all SRES scenarios. In some projections, arctic late-summer sea ice disappears almost entirely by the latter part of the 21st century
- Drought-affected areas will become larger
- Heavy precipitation events are very likely to become more common increasing flood risk
- Water supplies stored in glaciers and snow cover will be reduced over the course of the century

However, some regional and temporal patterns could be distinguished (figure 4.14). It is projected with high confidence that:

- Regional patterns:
    - Dry regions are projected to get drier: decrease in fresh water availability by 10–30% over some dry regions at mid-latitudes and in the dry tropics by 2050
    - Wet regions are projected to get wetter: increase in fresh water availability by 10–40% at high latitudes and in some wet tropical areas by 2050
- Temporal patterns:
    - Winter is projected to become wetter in northern latitudes but dryer in southern ones
    - Summer is projected to become drier in most areas

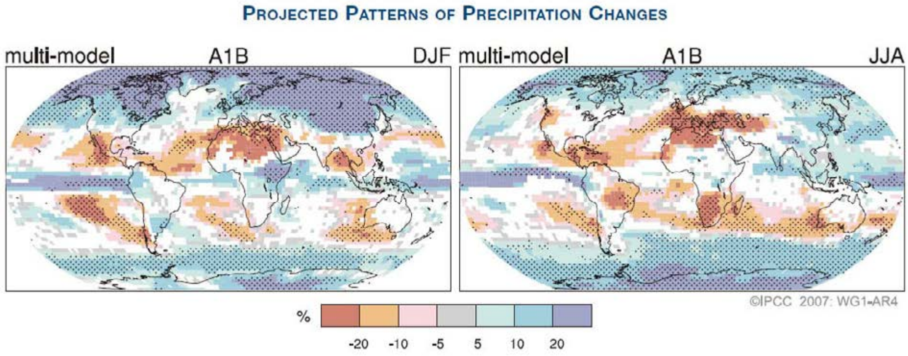

Figure 14: Projected relative changes in precipitation using SRES A1B scenario for 2020-2099 relative to 1980-1999. December to February (left) and June to August (right) (source: (IPCC, 2007))

Regarding to the extreme rainfall events, such as rainstorms and no-rain periods directly affecting drought and floods, the current observed trend and the future prediction show again regional-dependent tendency. According to NASA, in general is expected that rainstorms increase by 7.8% and the periods of no rain by 5.2% every 1ºC of global warming. Figure 4.15 shows the predicted heavy precipitation trend for the period 2080-2099 developed by IPCC (2007). The number of rainstorms increases mainly in northern latitudes and tropical zones around the equator, particularly in the Pacific Ocean and Asian monsoon regions. On the other hand, the deserts and arid regions of the southwest United States, Mexico, North Africa, Mediterranean countries, the Middle East and northwestern China in the North Pole; South Africa, northwestern Australia, coastal Central America and northeastern Brazil in the South Pole are the projected areas to be critically affected by no rain periods.

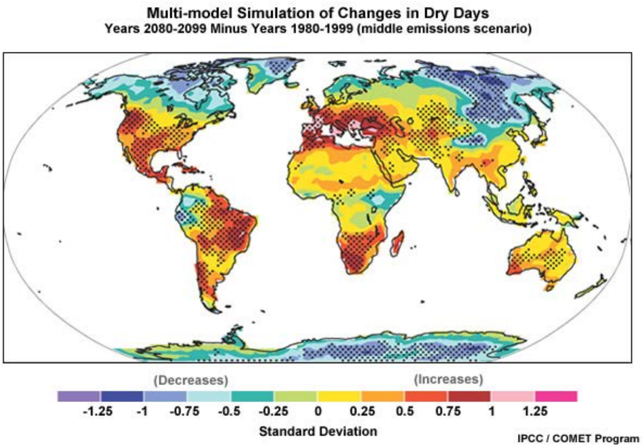

Figure 15: Distribution of precipitation intensity and dry days changes for 2080-2099 relative to 1980-1999. (source: (IPCC, 2007))

6.3.3 Water resources and climate change

The hydrometeorological records and climate projections developed show a future scenario characterized by water resources vulnerability and negatively affected by climate change, with wide-ranging consequences for humanity and ecosystems (figure 4.16). The conclusions of the International Symposium Time to Adapt – Climate Change and European Water Dimension (2007) give as an overall idea about present and future challenges on water resources management. As it states:

1. *Climate is changing. The scientific evidence conveys the clear message that this change will impact the water cycle and water resources worldwide. An increase in the frequency and intensity of extreme events such as floods and droughts is expected as well as long-term shifts in regional water balance and water availability. Both may have disastrous consequences for societies.*

2. *Changes in water resources will not only have significant adverse impacts on the drinking water supply and wastewater services, but also on other key economic activities such as agriculture, hydropower and other electricity production, tourism and navigation. These damaging effects will by far surpass minor benefits that may be experienced by individual regions or sectors.*

3. *Ecosystems and biodiversity are likely to suffer from climate-driven changes in hydrology. Ecosystem services play a key role for human and economic activities, and their long-term protection and preservation should be given priority.*

4. *Changes in climate will occur, even if climate protection measures are effectively implemented today. Although the magnitude of climate change impacts on the water cycle and water resources cannot be predicted exactly, scientific evidence is sufficient to urge immediate action.*

5. *Therefore, while climate change mitigation should remain a priority for policy-making, there is also an urgent need to develop strategies for adaptation to the already inevitable climate-change-driven changes in water resources at all levels of policy-making – from the European to national to local levels. There is now consensus on this among the science and policy communities.*

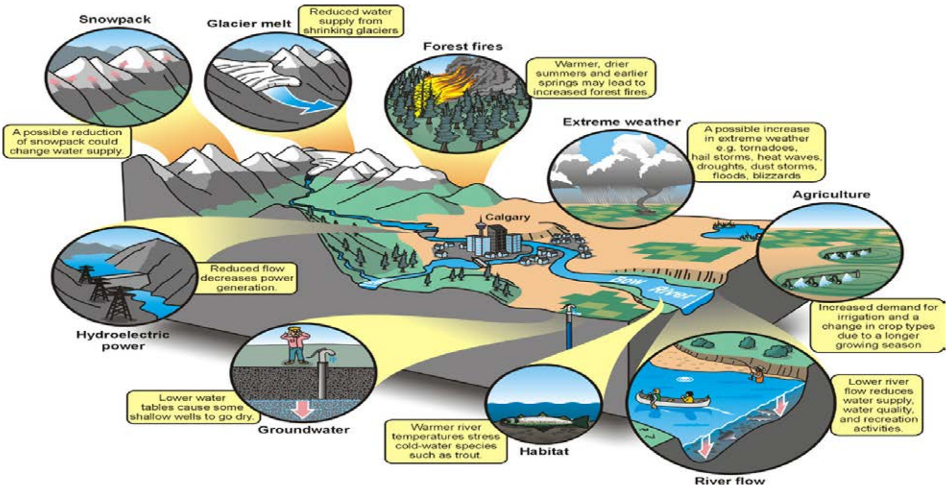

Figure 16: Interactions between climate change, hydrology, water resources and human and ecosystem funtions (source: (National Resources Canada, 2008))

The impacts of climate change on hydrology, water resource, ecosystems and human activity may include:

- Disaster risks enhancement due to extreme events such as drought, floods or forest fires.
- General decrease of water availability in rivers, lakes, aquifers, snowpack, etc.
- Negative affection of water quality with impacts to human, agriculture and ecosystem health.
- Decrease in the availability of water for consumption.
- Increased demand of water for agriculture due to changes in crops and longer growing season.
- Less water availability for business activities such as agriculture, industry, hydroelectric power, recreation, tourism, etc.
- Increase in the pre-treatment costs due to low water quality.

However, due to the uncertainties arising from the climate change predictions, models applied but also the singular resilience of societies and terrestrial and aquatic ecosystems, future projections developed about the impact of climate change on water resources at local or regional level are complex and highly temporally and spatially-dependent (figure 4.17).

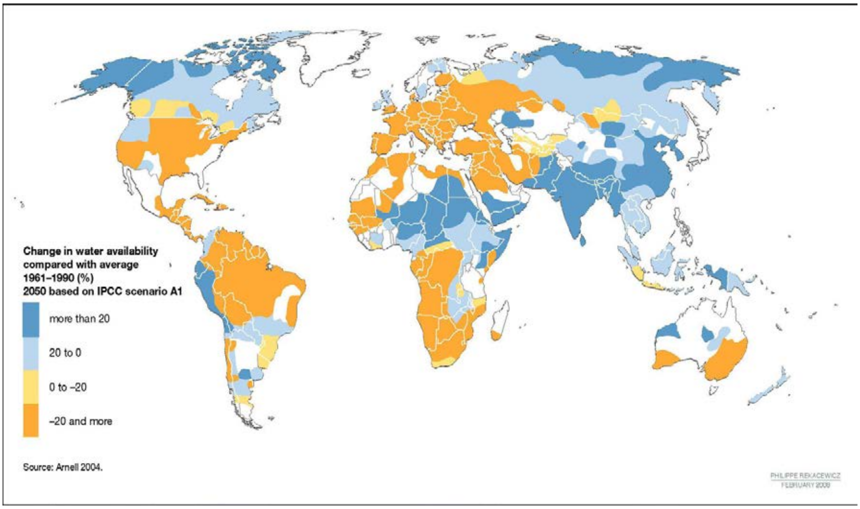

Figure 17: Change in wwater availability by 2050 (IPCC scenario A1) relative to 1961-1990 [source: Rekacewicz (2009a)]

As is mention by numerous researchers, the climate change can impact on water availability by modifying both quantity and quality of the water resources:

- Impacts on water quality include alteration of physical, chemical and biological water parameters which affects its consumption by societies and environments.
- Quantity changes affect the fresh water temporal and spatial availability for societies and ecosystems represented mainly by opposite extreme events.
    - Heavy rainfalls leading floods.
    - Water scarcity and drought after no-rainfall periods.

6.3.4 Useful links

- IPCC Fourth Assessment Report: Climate Change 2007 (AR4)
- Time to Adapt - Climate Change and the European Water Dimension

6.4 Water quality

Water resources quality influences directly its availability and use by society and environments. The impact of climate change on water quality could be:

- Related to temperature:
    - Affecting biogeochemical cycles.
    - Algae blooms reducing dissolved oxygen.
    - Cyanobacteria blooms after the reduction of dissolved oxygen.
- Related to flow volumes:
    - Change in the speed, residence time and dilution capacity of the water flows.
    - Rise in storm events which increase the occurrence of sewer overflows and polluted water discharges in the water bodies.

- An increase in erosion processes related to extreme rainfall events involving a rise in suspended particles, nutrients and pollutants from the transported sediments.

- Others:
  - Changes in crop management due to climate change involving an increase in fertilizers or pesticides.
  - An increase in wildfires involving a rise in erosion and suspended particles and nutrients from the transported sediments and ashes.
  - Sea level rise may affect ground water quality by increasing the salinity of rivers and causing saltwater intrusion into the coastal water bodies and groundwater resources.

Figure 18: Toxic algal bloom [source: U.S. Global Change Research Program (2009)]

Surface, ground and drinking water quality alterations are temporary and spatially dependent as it is climate change. For example, the decrease in river flow volumes in Mediterranean regions during the summer leads a decrease of the dilution capacity or the dissolved oxygen content, affecting water quality. On the other hand, the opposite trend but also an increase in suspended sediments, nutrients and chemical due to erosion exacerbation may be expected in northern latitude countries during the winter as a result of the increase in rainfall and water flow volumes.

Besides, as it was stated before, future projections developed about the impact of climate change on water quality at local or regional level are complex (Murdoch et al., 2000) and highly temporally and spatially-dependent due to the uncertainties arising from the climate change predictions, models applied but also the singular resilience of societies and terrestrial and aquatic ecosystems.

The main water physical, chemical and biological parameters affected by the climate change impact are:

- Temperature
- Suspended particles
- Nutrients
- Salt intrusion into groundwater bodies

6.4.1 Temperature

In general and according to the future projections, an increase in water temperature is expected as a result of the global warming (figure 4.19). Chemically, water temperature is related directly to the speed of the biochemical reactions. The rise in water temperature may affect processes in different ways (Arnell, 1998). Increase in water quality could be expected as a direct result of water warming as biological processes and aeration rate are accelerated by this alteration. However, this trend is offset by the decrease in oxygen hold capacity by water, its consumption during faster biochemical reactions and the decrease in flow volumes (Mimikou et al., 2000).

Lakes and stagnant water ecosystems are less resilient to the impacts of global warming on water temperature due to the minor vertical and horizontal flows. The increase in air temperature may lead a reduction in convective and wind-mixing fluxes and, as a consequence, stratification of the water body, a reduction in the oxygen input in deeper water tables and bottom water anoxia.

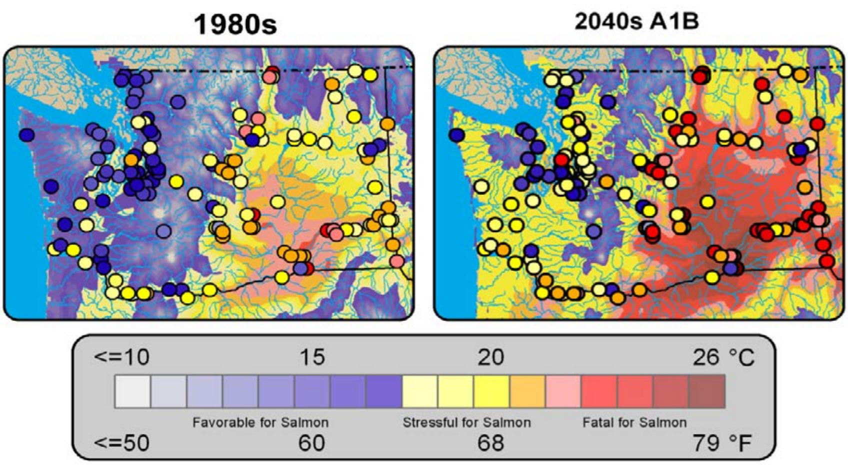

Figure 19: Air (coutinous colors) and water (colored dots) summer temperature for the 1980s and the 2040s [source: (Mantua et al., 2010)]

Regarding to the drinking water, global warming may exacerbate of mitigate water quality depending on local and temporal factors by affecting (Callow and Petts, 1994):

- Nutrient cycle and delivery rates.
- The mobility and toxicity of contaminants.
- The efficacy of water treatments.
- Its organoleptic properties (taste and odour).
- Pathogen activity.

6.4.2 Suspended sediments, nutrients and pollutants

An increase of suspended sediments in the superficial water flows is expected as a consequence of the climate change enhancement of erosion processes. The increase of extreme events such as rainstorms or mega-wildfires, the decrease in water volumes affecting dilution capacity and residence time and the human activity as for example massive land use changes or intensive agricultural practices may unbalance the hydrological processes and lead higher sediment yields in the runoff and water flows (e.g. Nearing et al., 2005). Sediments are expected to:

- Transport and release loads of nutrients, pesticides, heavy metals and other contaminants.
- Decrease light penetration into the water.
- Affect photosynthesis.
- Influence water temperature.

The same general trend is expected regarding to nutrients. Future projections show an increase in water nutrient load due to climate change and human activity influence of their cycles and delivery rates in different ways (Bouraoui et al., 2002). Moreover, their concentration and residence time could increase due to the less dilution capacity due to the decrease in water volumes projected for some regions. Besides, some processes are temperature dependent such as nitrification, which is inversely related to this parameter.

Regarding to groundwater resources, the projected increase in heavy storms and related floods together with the poorly managed industrial and agricultural activity may account for the mobilization of pollutants from contaminated surface areas which usually remain dry or crop soils rich in fertilizers and pesticides leading their transport into the groundwater bodies and affecting their quality. Despite the aquifer bodies are considered as relative robust in the face of climate change due to their partial isolation and soil buffering effect, it is important to point out that once contaminated their treatment and recovery is highly technical and cost-demanding.

6.4.3 Nutrients and eutrophication

Especially important are N and P due to their influence on eutrophication processes (figure 4.20). Despite the clear trend of nutrient load in the water bodies, eutrophication predictions should be evaluated from the point of view of the contributing individual components affected by climate change as it show a more complex prediction (Whitehead et al., 2009). The increase in nutrient loads due to higher inputs and lower water volumes is expected to lead bacterial growth in water bodies. Besides, the general water temperature increase and the decrease of water turbidity and increase in light penetration during summer as a consequence of flow volumes fall and residence time increase allowing sedimentation of suspended particles is also expected to enhance bacteria growth. As a consequence, biological oxygen demand (BOD) is expected to increase and dissolved oxygen decrease causing impacts on the aquatic ecosystems and affecting water quality and health risks to humans.

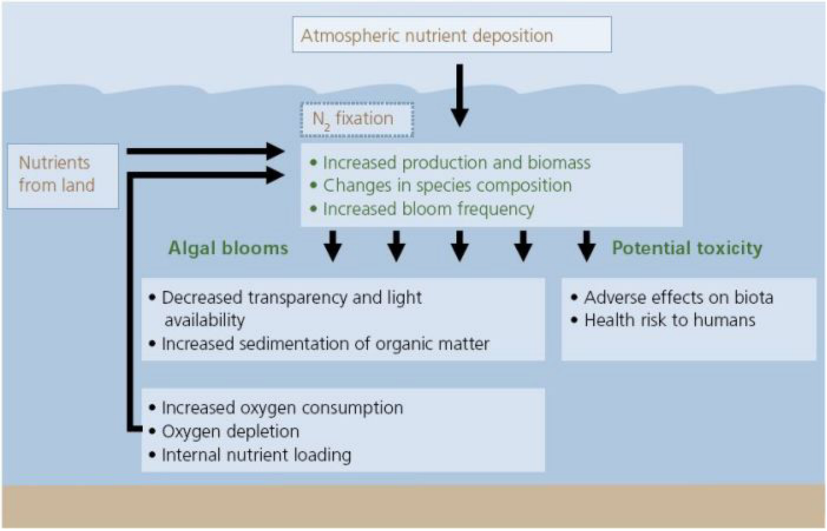

Figure 20: Eutrophication processes [source: (Helsinki Commission, 2010)]

Despite this general trend, the spatial and temporal dependence of climate change impacts stated in the previous sections could affect this process. The local impact of eutrophication will depend on:

- Local weather parameters patterns affecting water mixing and oxygenation processes.
    - Rainfall
    - Temperature
    - Wind

- Factors affecting erosion processes and suspended particles and nutrient in the runoff flow:
    - Soil type and erosionability
    - Topography
    - Land use
    - Vegetation cover
    - Wildfires
    - Agricultural practices and use of fertilizers and pesticides
- Characteristics of the water body affecting flow speed, residence time and oxygenation processes:
    - Volume
    - Flow volume and speed
    - Shape
    - Depth
    - Water inputs and outputs

6.4.4 Salt intrusion into groundwater and coastal water bodies

One of the main problems affecting coastal surficial and groundwater bodies is the saltwater intrusion or the replacement of fresh water by marine water due to the movement of the later into the former through the existing interface layer between them in coastal areas. Regarding to aquifers, the salt intrusion processes generally depends on the balance between (figure 4.21):

- Aquifer volume: recharge and exploitation of the groundwater resources impact on the balance between water input and output and, thus, water volume. A decrease in water flow to the aquifer and/or an increase in water extraction from it may lead an increase in saltwater intrusion.

- Sea level: the alteration of the sea level may affect directly the balance between salt and freshwater by inducing both saltwater intrusion and inundation.

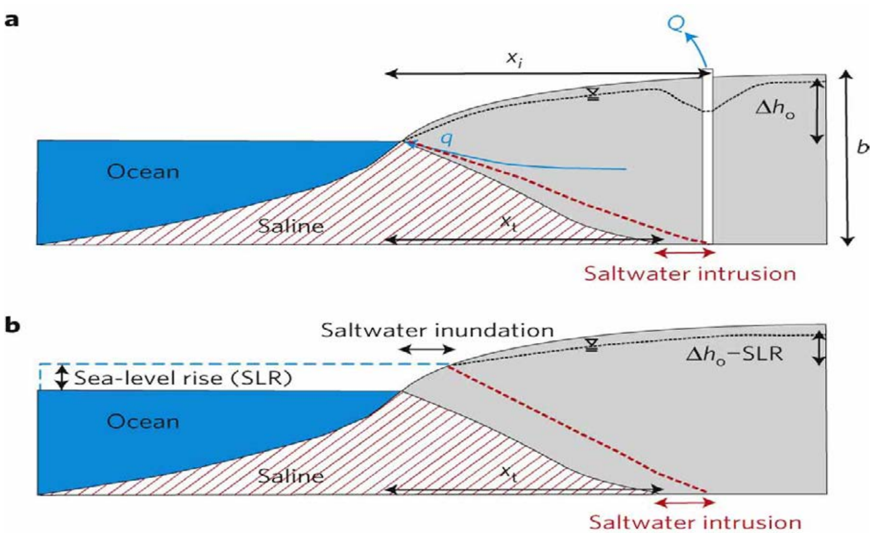

Figure 21: Modeled impacts of groundwater extraction (a) and sea-level rise (b) [source: (Ferguson and Gleeson, 2012)]

Due to the high temporal and spatial dependence of the alteration of climate and social parameters due to climate change, the local impact of this process on coastal water bodies' quality is expected to be highly complex and dependent of the regional and temporal behaviour of the cited factors affecting this process. According to the stated before, the impact of climate change on coastal water bodies depends on the behaviour of:

- Climatic parameters affecting freshwater balance.
  - Precipitation: an increase in the annual precipitation may account for a decrease in salt intrusion but an increase in extreme events or a decrease in precipitation may lead the opposite trend.
  - Temperature: the global warming is expected to affect the evapotranspiration processes by reducing soil moisture and water input into the aquifers.

- Social demands:
    - Water demand: the expected increase in population, industrial processes and global warming is expected to lead a general rise in water demand which could affect negatively the balance between salt and freshwater inducing salt intrusion in coastal water bodies.
    - Land use and agricultural practices: land use and vegetation change may alter the hydrological cycle by modifying the evapotranspiration process and affecting the aquifer recharge.

6.4.5 Useful links

- Water Quality and Future Generations
- Water Quality and the Environment
- Eutrophication | Ecology and Environment | the virtual school

6.5 Floods

Floods are sudden changes in water level exceeding its natural confinement and covering a portion of land not previously covered. They are considered the main threat to humanity among the geological hazards affecting millions of people every year.

Floods are natural processes which occur in river systems on a regular basis generally by melting snows or heavy rains, but they may occur anywhere related to other exceptional natural disasters such as hurricanes and cyclones including rain storms, tsunamis in coastal environments or volcanic eruptions melting snows, or even human induced causes including incorrect infrastructure planning or wrong land use decisions (figure 4.22).

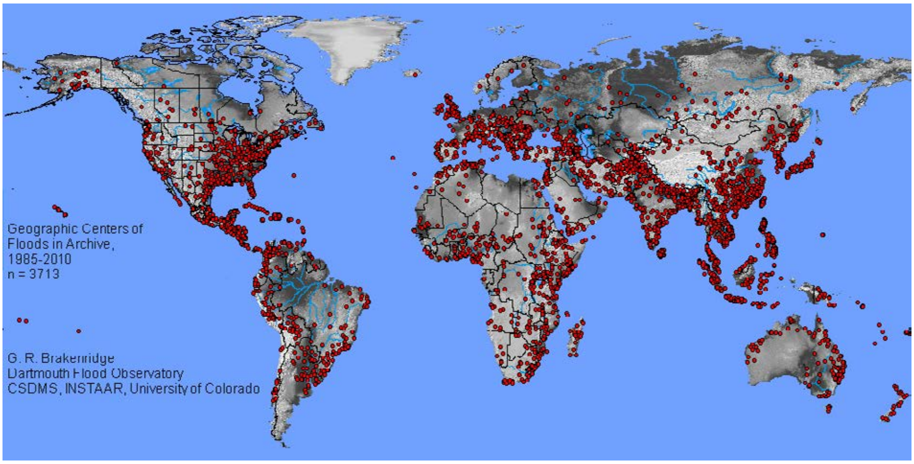

Figure 22: Flood occurrence (1985-2010) [source: (Brakenridge, 2010)]

6.5.1 Factors involved in flood formation

The destructive power of a flood is mainly due to two factors. First, there is the power of erosion and transport of material by the water when a rise in its level occurs. Secondly, there is the fact that floodplains in their morphology and natural wealth provide very favourable conditions for human settlements.

Figure 4.23: Missouri River flooding (USA) on July 30, 1993 (source: (U.S. Geological Survey, 2011))

Flooding can happen anywhere, but certain areas are especially prone to serious flooding. There are two types of factors involved in flood formation:

- Conditioning Factors
  - Morphology: the flat configuration of the ground facilitates the expansion of the water layer whilst sudden changes in slope favour sudden increases in the velocity of water and its concentration.
  - Terrain: the lithological composition of the soil determines its drainage and erosion capacity, this determines whether rivers may carry more or less load during a period of overflow.
  - River morphometry: river systems may have different morphologies: braided, meandering, rectilinear, which can determine the velocity of water, overflow preferential areas, etc.
- Triggering factors
  - Weather and climate change: the intensity of rainfall or melting snow may exceed the capacity of drainage system and cause an overflow.
  - Seismic: earthquakes can trigger tsunamis that can cause severe flooding in the coastal zone.
  - Deforestation: the lack of a well-developed vegetation cover increases water runoff on the ground.
  - Obstruction of the bed: this can occur when waste, trunks or tailings act as a stopper, obstructing the water and causing flooding. These blockages can also be caused by the passage of lava flows.
  - Paving and bed confinement: these lead to an increase in the speed of runoff and reduce (or cancel) the infiltration of water into the subsoil. Moreover, these favour the deposition of materials on the channel bottom, which then fill and collapse over time thus increasing the topographic level where water circulates.
  - Defective flood defences both in coastal and river areas.

6.5.2 Climate change and floods

Despite the temporal and regional dependence, according to the future prediction an increase in storm events and severity and intensity of the rainfall is expected in most temperate and humid regions of the world. Besides, the projected sea level rise is expected to lead an immersion process of the coastal lands in areas where sea defences may be overtopped. As a result of these general trends, flood risk is expected to increase considerably in the future over the world (figure 4.24). Regarding to the timing of the flood risk, it is predicted it shifts from snowmelt in spring to summer, autumn or even wintertime in Europe (Bergstrom et al., 2001). The severity of this change is shown to be regionally dependent but also critically influenced by the SRES scenario used.

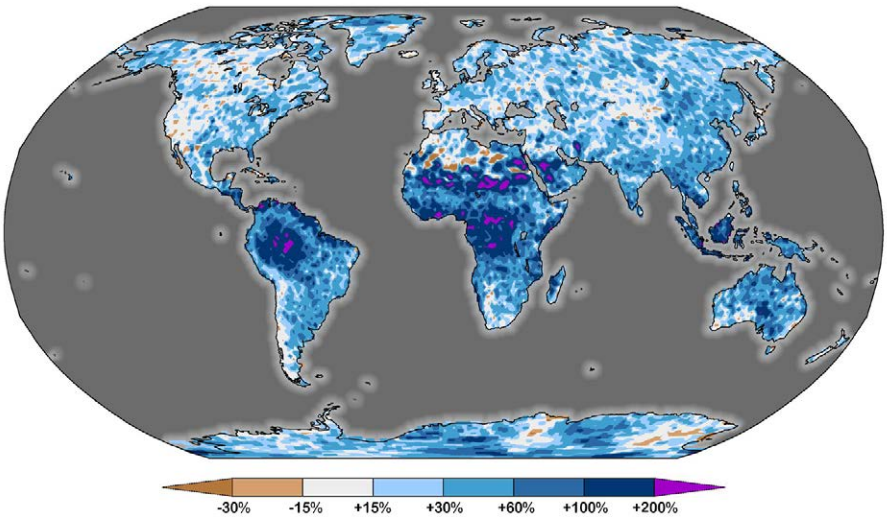

Figure 24: Projection of the change in the flash flood occurrence during the 21st (source: (Dirmeyer, 2011))

Regarding to flood damages, future projection show they will depend more on human decision and population trends such as settlement planning, land-use decisions, flood forecasting, warning, preventions and response systems, and the value of structures and other property located in vulnerable areas (Pielke and Downton, 2000), than on the impacts of climatic change. Besides, human activity may directly or indirectly influence flood occurrence and related risks by:

- Affecting land and river morphology through civil engineering jobs.
- Modifying land use by deforestation which may leads increases in water runoff.
- Inducing obstruction of the river bed by providing waste, poor maintenance or reducing river bed.
- Reducing terrain drainage by paving and bed confinement.
- Locating housing and infrastructures in flood-prone areas.

According to most studies, the projected economic losses by 2080 related to floods will range from 1.5 to 20-fold the current losses due to this natural disasters depending on the region and SRES scenario used to model the climate change (see e.g. Hall et al., 2005).

The predicted regional increase in extreme events due to climate change will alter on different sector such as water resources, agriculture, ecosystems, human health, industry activity and social development (Economic Commission for Europe, 2009). The main projected impacts by sector are quoted below.

Table 3: Examples of projected impacts of heavy rainfalls (Source: (Economic Commission for Europe, 2009))

Water resources	Agriculture/Ecosystem	Health	Industry/Society
· Flooding Adverse effects on quality of surface and groundwater due to sewer overflows · Contamination of water supply Water scarcity may be relieved	Damage to crops Soil erosion Inability to cultivate land due to waterlogging of soils	Increased risk of deaths, physical injuries and infectious, respiratory and skin diseases Risk of psychological disorders	Disruption of settlements, commerce, transport and societies due to flooding, migration Pressures on urban and rural infrastructures Loss of property

6.5.3 Flood effects

The primary effects of floods are those due to direct contact with the floodwaters. These are:

- Increased sediment load due to the high velocity of floodwaters. When the floodwaters retreat, velocity is generally much lower and sediments are deposited undermining bridge structures, levees and buildings causing their collapse.
- Transport of larger particles (rocks, sediments, branches or logs, but also vehicles, houses, bridges, etc.) as suspended load due to higher water velocities.
- Risk to human lives due to the high flow velocity and suspended materials.
- Water entering human built structures causing water damage.
- Flooding of farmland resulting in crop and livestock loss.
- Humans that get caught in the high velocity floodwaters are often drowned by the water.
- Floodwaters can concentrate garbage, debris and toxic pollutants that can cause secondary effects of health hazards.

Figure 25: Road blocked by floods (source: (Civil Defense New Zealand Government, 2007))

Secondary effects refer to those that occur as a result of the primary effects:

- Pollution of drinking water supplies especially if sewerage treatment plants are flooded resulting in disease and other health effects, especially in under developed countries.
- Gas and electrical service may be disrupted.
- Transportation systems may be disrupted, resulting in shortages of food and cleaning-up supplies. In under developed countries, food shortages often lead to starvation.

Long-term effects (tertiary effects) of floods include:

- Changes in the location of river channels as the result of flooding, new channels develop, leaving the old channels dry.
- Destruction of farmland by sediment deposited on farmland (although silt deposited by floodwaters can also help to increase agricultural productivity).
- Job losses due to the disruption of services, destruction of business, etc. (although jobs may be gained in the construction industry to help rebuild or repair flood damage).
- Increase in insurance rates.
- Destruction of wildlife habitat.

On average, each year, 196 million people, in over 90 countries, are vulnerable to catastrophic flooding. Predictably, vulnerability to such disasters will increase in coming years due to climate change. Countries with high vulnerability to floods include Somalia, Morocco and Yemen. Venezuela also belongs to this group but due to a single event. In addition, a larger number of people are exposed to floods of lesser magnitude. Normally, these losses are not taken into account in estimates of damage because they are of low severity. However, they do hinder the development of the affected areas.

6.5.4 Useful links

- A new EU Floods Directive
- Dartmouth Flood Observatory, University of Colorado
- The IPCC, Climate Change, Floods & More - Questions for Gerald Meehl (NCAR) - UConnect Interview
- Flood Lines - Urban Adaption to Climate Change in Hoi An, Vietnam

6.6 Water scarcity and drought

Water scarcity is broadly understood as the lack of adequate quantities of water for human and environmental consumption. Water scarcity is affected by the supply of fresh water to the population and environment (rainfall patterns, temperature and evapotranspiration, floods, droughts, etc.) but also by their demand and consumption. Regarding to drought, they could be divided into:

- Meteorological drought: when precipitation is below the average.
- Hydrological drought: when river, lakes and groundwater show a low water level.
- Agricultural drought: when soil moisture is below wilting point.
- Environmental drought: a combination of the above mentioned.

Nowadays, approximately 1.2 billion people do not have access to safe drinking water and the models project that by 2025 this figure will reach 2.7 to 3.5 billion people if mitigation actions are not taken (figure 4.26). African countries are those showing the greatest vulnerability to drought. However, methodological difficulties prevent a complete study and the publishing of solid conclusions about this risk and specific to any country.

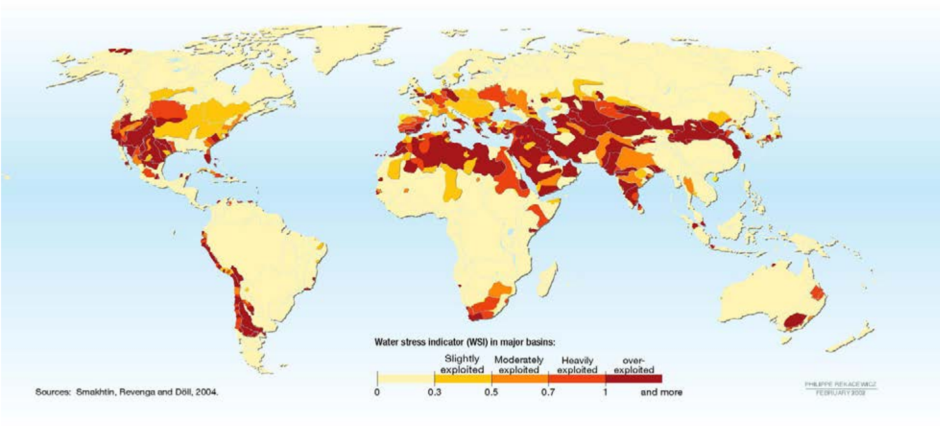

Figure 26: Water scarcity in major basins [source: Rekacewicz (2006)]

6.6.1 Measurements of water scarcity

Despite the growing concern about water scarcity and droughts during the last decades, there is no consensus on the definition and measurement of this situation. The four main approaches regarding to the assessment of the degree of water stress are (White, 2012):

1. The Water Stress Index (Falkenmark et al., 1989): It measures water scarcity in terms of total water resources availability per person per year in a region or country. It classify water scarcity in three different levels:

    - Vulnerable: the renewable water in the region is below 2.500 m^3 per person per year.
    - Water stress: when the figure is below 1.700 m^3 per person per year.
    - Water scarcity: when the figure is below 1.000 m^3 per person per year.
    - Absolute water scarcity: when the figure is below 500 m^3 per person per year.

This is one of the most popular methods to measure water stress due to its straightforwardness and low data requirements. However, its simplicity lead that this approach has some limitation:

- It ignores regional-dependence of water availability.
- It does not take into account water accessibility or water quality.
- It excludes water treatments (e.g. desalinization) as water resource suppliers.
- It takes into account water availability but not the dissimilar water demand in different countries or regions.

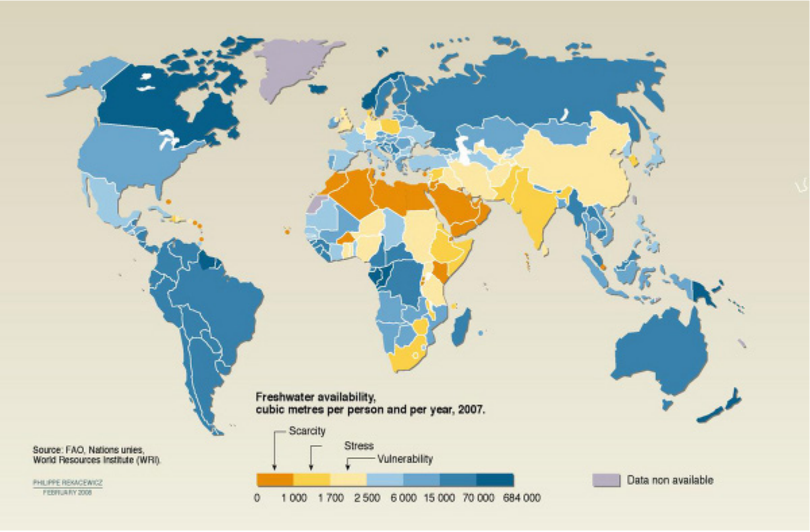

Figure 27: Water Stress Index per country (2007) (source: (Rekacewicz, 2008))

2. **<u>Criticality ratio (OECD, 2009):</u>** it takes into account that all countries show different water demand and defines water scarcity in terms of the ratio withdrawn water - available water. The threshold of water scarcity for a region is overtaken when the withdrawals are 40% of the availability. The main limitations related to this index are that:

- It excludes water treatments (e.g. desalinization) as water resource suppliers.
- It ignores water reusing and recycling processes.
- It ignores the capacity of countries or regions to adapt to lower water availability.

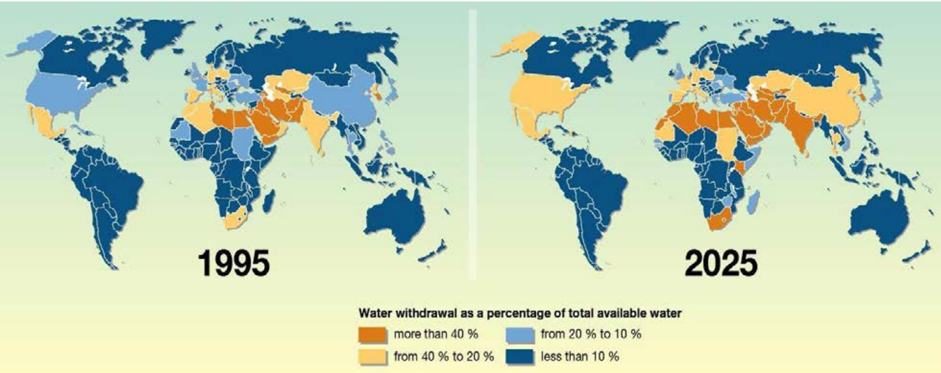

Figure 28: Water withdrawals-available water ratio projection (1995-2025) [source: (Rekacewicz, 2009b)]

3. <u>**International Water Management Institute (IWMI) approach (Seckler, 1998):**</u> similar to the previous one, it tries to solve the previous deficiencies by including water infrastructures (e.g. desalinization plants) into the water availability assessment; reuse and recycle concepts by using water consumption instead of total withdrawals; and adaptive capacity of the region or country by measuring its potential to develop water infrastructure and efficiency improvements. IWMI consider that two types of water scarcity:

   - Economical water scarcity: when a country or region is predicted to be unable to meet it future demand without investment in water infrastructure and efficiency.

- Physically water scarcity: when is predicted to be unable to meet its future demand even with such investment.

As some degree of complexity and sophistication has been including in this approach to solve the problems of the previous ones, its main limitations are that:

- Time and data requirements are considerably higher than in previous approaches.
- It still ignores country or region capacity to adapt to a lesser water consumption.

4. **Water poverty index (Sullivan et al., 2003):** this approach takes into account wealth levels into the evaluation of water scarcity by measuring:

- The access to water.
- The water quantity, quality and variability.
- The amount of water used for domestic, food and productive purposes.
- The capacity for water management.
- The environmental issues related to water consumption.

This index was developed to assess water scarcity at local or regional levels due to its high complexity and demand of available data.

6.6.2 Climate change and water scarcity

The projected influence of climate change on temperature, precipitation and sea-level rise may aggravate the current water scarcity and drought affecting most semi-arid and arid environments or induce drought periods in more humid or temperate areas. Climate change may affect the two parameters involved in water scarcity: fresh water availability and demand. As it was stated in previous sections, the impact of climate change on temperature, precipitation and sea-level rise may affect both the water quantity and quality and thus its availability for consumption. Besides, climate change alteration of evapotranspiration patterns and water demand by population, industry and agriculture may induce water scarcity by increasing water consumption. The most obvious effects of climate change on fresh water availability may be:

- A decrease in the natural water storage capacity from snowpack melting.
- A decrease in surface and ground-water bodies especially in the subtropics and mid-latitudes due to changes in precipitation patterns and intensity, including droughts and floods.
- Impacts on surface and ground-water quality including suspended sediments and pollutants, algae blooms, eutrophication.
- Sea-salt intrusion into aquifers and coastal water bodies due to sea-level rise reducing their quality.
- A reduction of the natural water filtration ability and buffering due to the impact of temperature increases changes in precipitation patterns, and prolonged droughts on the ecosystems.
- The affection of the water supply infrastructure due to floods, extreme events and sea level rise.
- Increase of the water demand water for human, agricultural, livestock and industrial due to temperature rise and changes in precipitation patterns.

Droughts have increased their frequency and affected area in the last decades in tropical and subtropical regions mainly due to the precipitation decrease and temperature increase altering atmospheric circulation, enhancing evapotranspiration and reducing soil moisture and snowpack. Extreme events such as heatwaves have also contributed to the last observed changes in drought frequency (see e.g. Bates et al., 2008). Current projections show that the Mediterranean area is one of the world´s regions where water resources will be more negatively affected by climate change (see e.g. Rosenzweig et al., 2004; Vicente-Serrano et al., 2004). According to most studies, the combination of increasing temperatures and decreasing precipitation projected for this region may lead to a substantial unbalancing of the water discharge-demand ratio and, thus, to induce or aggravate the current water scarcity in this region. As you can see in the figure 4.29, current droughts with100-year return period will be frequent every 10 years by 2070 in parts of Spain, Portugal, France, Poland and Turkey (Lehner et al., 2005).

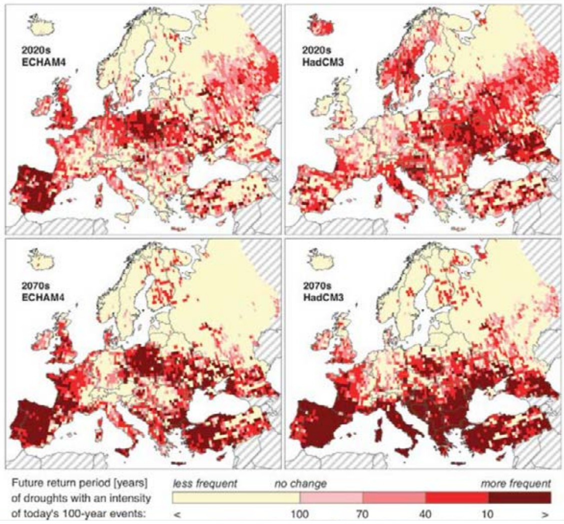

Figure 29: Projected change in the recurrence of the current 100-year return period droughts [source: (Lehner et al., 2005)]

6.6.3 Impacts of water scarcity and droughts

Some expected future impacts of water scarcity and drought due to climatic drivers such as rise in temperature and precipitation variability based on projections to 21st century are summarized below by sector (Bates et al., 2008):

1. Water resources:

   a Changes in run-off.

   b More widespread water stress.

   c Increased water pollution due to lower dissolution of sediments, nutrients, dissolved organic carbon, pathogens, pesticides and salt, as well as thermal pollution.

   d Salinization of coastal aquifers.

2. Agriculture/Ecosystem
   - a Land degradation and desertification.
   - b Lower yields/crop damage and failure.
   - c Increased livestock deaths.
   - d Increased risk of wildfire.

3. Health
   - a Increased risk of food and water shortage.
   - b Increased risk of malnutrition.
   - c Increased risk of water and food-borne diseases.

4. Industry/Society
   - a Water shortages for settlements, industry and societies.
   - b Reduced hydropower generation potentials.
   - c Potential for population migration.

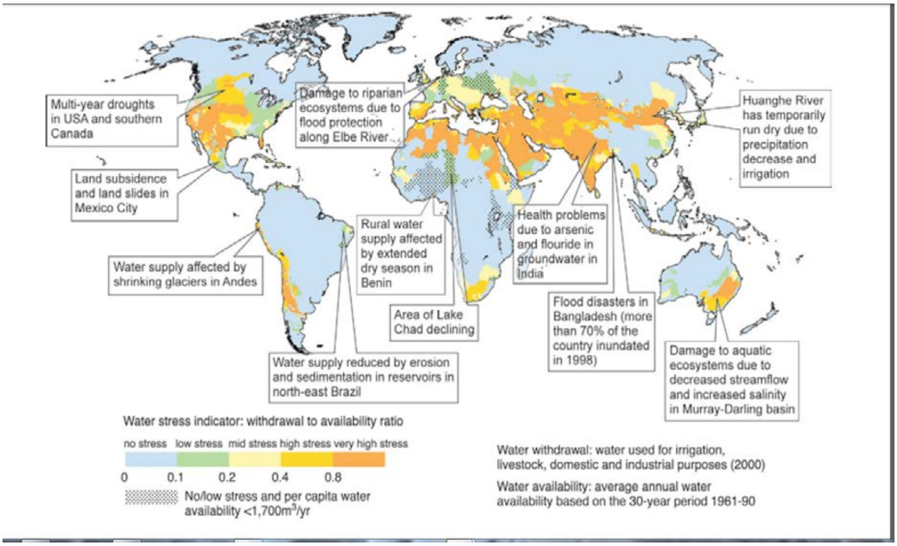

Figure 30: Water stress map and examples of freshwater resources vulnerabilities and their management [source: (Bates et al., 2008)]

6.6.4 Useful links

- Understanding water scarcity: Definitions and measurements
- Water Scarcity & Droughts in the European Union
- Climate change and water
- Water Scarcity

7 EUROPEAN LEGISLATION

7.1 Introduction

The European Union has developed a complete set of legislative tools for the State members in order to protect their water resources. It affects water usage, marine pollution, inland waters and discharge of substances. Besides, it range from general rules or frameworks such as the Water Framework Directive to regionally specific laws as for example the Environment Strategy for the Mediterranean; from Directives to Communications; from general recommendations such as water management to specific prohibitions as for example the use of pollutant compounds on ships paints; from marine to fresh water; from industrial use of water such as industrial emissions to recreation use as for example bathing.

7.2 European legislation

The European legislation on water resources may be divided according to the stated before as follows:

1. General Framework
2. Specific use of water
3. Marine pollution
4. Regional waters
5. Discharge of substances

Next sections will broaden the main European legislation related to water resources protection and management by providing the short official summary and the referred act established by the European Union (European Commission, 2013).

7.2.1 General Framework

Water protection and management (Water Framework Directive)

The European Union (EU) has established a Community framework for water protection and management. Firstly, Member States must identify and analyse European waters, on the basis of individual river basin and district. They shall then adopt management plans and programmes of measures adapted to each body of water.

Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy.

Pricing and long-term management of water

The Commission is presenting questions and options in connection with defining water pricing policies enabling the sustainability of water resources to be boosted.

Communication from the Commission to the Council, European Parliament and Economic and Social Committee: Pricing and sustainable management of water resources.

Flood management and evaluation

Communication from the Commission to the Council, European Parliament and Economic and Social Committee: Pricing and sustainable management of water resources.

Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks.

Droughts and water scarcity

The Commission provides guidelines for addressing sporadic drought and medium- or long-term water scarcity. The guidelines deal with water pricing, water allocation, drought prevention and rapid response in the event of a drought, as well as high-quality information and technological solutions tackling water scarcity and droughts.

Commission Communication of 18 July 2007: "Addressing the challenge of water scarcity and droughts in the European Union".

Urban waste water treatment

Due to their volume, discharges of urban waste water are the second most serious cause of water pollution in the form of eutrophication. This Directive seeks to harmonise measures relating to the treatment of such waters at Community level.

Council Directive 91/271/EEC of 21 May 1991 concerning urban waste water treatment.

7.2.2 Specific use of water

Quality of drinking water

The European Union (EU) is defining the essential quality standards which water intended for human consumption must meet.

Council Directive 98/83/EC of 3 November 1998 on the quality of water intended for human consumption.

Bathing water quality (until 2014)

The European Union (EU) lays down rules for the monitoring, assessment and management of the quality of bathing water and for the provision of information on that quality. The aim is twofold, to reduce and prevent the pollution of bathing water, and to inform European citizens of the degree of pollution.

Council Directive 76/160/EEC of 8 December 1975 concerning the quality of bathing water.

Bathing water quality

The European Union (EU) introduces new legislation aimed at improving bathing water quality. This Directive enables water monitoring and management measures to be improved, and information to be made available to the public.

Directive 2006/7/EC of the European Parliament and of the Council of 15 February 2006 concerning the management of bathing water quality and repealing Directive 76/160/EEC.

Water suitable for fish-breeding

Directive 2006/44/EC lays down quality criteria applying to water-courses and lakes. Compliance with these criteria is essential in order to maintain or improve water quality and to safeguard fresh water fish species.

Council Directive 2006/44/EC of 6 September 2006 on the quality of fresh waters needing protection or improvement in order to support fish life.

Quality of shellfish waters

The European Union establishes compulsory quality criteria for Member States' shellfish waters.

Directive 2006/113/EC of the European Parliament and of the Council of 12 December 2006 on the quality required of shellfish waters.

7.2.3 Marine pollution

Strategy for the marine environment

This Directive establishes a common framework and objectives for the protection and conservation of the marine environment. In order to achieve these common objectives, Member States will have to evaluate requirements in the marine areas for which they are responsible. They will then have to draw up and implement coherent management plans in each region, and then monitor their application.

Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for Community action in the field of marine environmental policy (Marine Strategy Framework Directive).

Maritime safety: compensation fund for oil pollution damage

This proposal aims to improve the liability and compensation arrangements for pollution damage caused by ships.

Proposal for a regulation of the European Parliament and of the Council on the establishment of a fund for the compensation of oil pollution damage in European waters and related measures.

Maritime safety: prevention of pollution from ships

The Community legislation on maritime safety must be adapted at regular intervals to take account of the amendments or the protocols to the international conventions, new resolutions or changes to the codes and compendia of existing technical rules.

Directive 2002/84/EC of the European Parliament and of the Council of 5 November 2002 amending the Directives on maritime safety and the prevention of pollution from ships.

Ship-source pollution and criminal penalties

The European Union creates a legal framework for imposing penalties in the event of discharges of oil and other noxious substances from ships sailing in its waters.

Directive 2005/35/EC of the European Parliament and of the Council of 7 September 2005 on ship-source pollution and on the introduction of penalties, particularly criminal penalties, for infringements.

Maritime safety: prohibition of organotin compounds on ships

This regulation aims to prohibit organotin compounds (anti-fouling paints) on all ships entering port in the Community in order to reduce or eliminate the adverse effects of these products on the marine environment and human health.

Regulation (EC) No 782/2003 of the European Parliament and of the Council of 14 April 2003 on the prohibition of organotin compounds on ships.

Maritime safety: Bunkers Convention

This Decision aims to authorise the Member States to become Contracting Parties to the 2001 International Convention on Civil Liability for Bunker Oil Pollution Damage.

Council Decision 2002/762/EC of 19 September 2002 authorising the Member States, in the interest of the Community, to sign, ratify or accede to the International Convention on Civil Liability for Bunker Oil Pollution Damage, 2001 (the Bunkers Convention).

7.2.4 Regional waters

European Union Strategy for Danube Region

Following a request from the European Council, the Commission presents a strategy aimed at developing the Danube Region in a coherent and sustainable way. Emphasis is placed on mobility, energy, innovation, the environment, risk management and security.

Communication from the Commission to the European Parliament, the Council, the Economic and Social Committee and the Committee of the Regions of 8 December 2010, European Union Strategy for Danube Region.

Baltic Sea Strategy

The Commission establishes a strategy to deal with the deterioration of the Baltic Sea, to improve the quality of transport networks and remove obstacles to trade.

Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions of 10 June 2009 concerning the European Union Strategy for the Baltic Sea Region.

Environment strategy for the Mediterranean

The Commission outlines the essential features of a coordinated strategy for the Mediterranean basin to protect the marine environment and the coastline of this region and to reduce pollution by 2020. This strategy is based on enhanced cooperation between the countries concerned in the political, financial and technical arenas, and provides for the accomplishment of targeted activities, planned within a common initiative known as "Horizon 2020".

Communication from the Commission of 5 September 2006 entitled: "Establishing an environment strategy for the Mediterranean".

Strategy to improve maritime governance in the Mediterranean

The strategy adopted by the European Commission in November 2009 meets different maritime challenges (security, fisheries, aquaculture, environmental protection, climate change, etc.) facing the Mediterranean basin. It is based on improving governance of maritime affairs which should balance economic development with protection of the environment. The success of this strategy requires enhanced cooperation with the third countries concerned.

Communication from the Commission of 11 November 2009 - Towards an Integrated Maritime Policy for better governance in the Mediterranean.

Black Sea Synergy

The Black Sea region, which includes Bulgaria and Romania, occupies a strategic position between Europe, Central Asia and the Middle East. The European Union intends to support regional commitments tending to increase mutual confidence and remove obstacles to the stability, security and prosperity of the countries in this region.

Communication from the Commission to the Council and the European Parliament of 11 April 2007 - Black Sea Synergy - A new regional cooperation initiative.

Danube - Black Sea region

Highlight actions to be taken to improve environmental quality in the Danube - Black Sea region and the outline of a strategy aimed at protecting the environment of the region.

Communication from the Commission: Environmental cooperation in the Danube - Black Sea region.

7.2.5 Discharge of substances

Industrial emissions

The European Union (EU) defines the obligations to be met by industrial activities with a major pollution potential. It establishes a permit procedure and lays down requirements, in particular with regard to discharges. The objective is to avoid or minimise polluting emissions in the atmosphere, water and soil, as well as waste from industrial and agricultural installations, with the aim of achieving a high level of environmental and health protection.

Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control).

Integrated pollution prevention and control (until 2013)

The European Union (EU) defines the obligations with which industrial and agricultural activities with a high pollution potential must comply. It establishes a procedure for authorising these activities and sets minimum requirements to be included in all permits, particularly in terms of pollutants released. The aim is to prevent or reduce pollution of the atmosphere, water and soil, as well as the quantities of waste arising from industrial and agricultural installations, to ensure a high level of environmental protection.

Directive 2008/1/EC of the European Parliament and of the Council of 15 January 2008 concerning integrated pollution prevention and control.

Environmental quality standards applicable to surface water

The Commission establishes environmental quality standards so as to limit the quantity of certain chemical substances that pose a significant risk to the environment and to health in surface water in the European Union (EU). These standards are coupled with an inventory of discharges, emissions and losses of these substances in order to ascertain whether the goals of reducing or eliminating such pollution have been achieved.

Directive 2008/105/EC of the European Parliament and of the Council of 16 December 2008 on environmental quality standards in the field of water policy, amending and subsequently repealing Council directives 82/176/EEC, 83/513/EEC, 84/156/EEC, 84/491/EEC, 86/280/EEC and amending Directive 2000/60/EC.

Protection of groundwater against pollution

The European Union is establishing a framework to prevent and control groundwater pollution. This includes procedures for assessing the chemical status of groundwater and measures to reduce levels of pollutants.

Directive 2006/118/EC of the European Parliament and of the Council of 12 December 2006 on the protection of groundwater against pollution and deterioration.

Detergents

The legislation on detergents permits improved protection of the environment by safeguarding water systems from the harmful effects of certain substances found in detergents. It also increases consumer protection through more complete labelling which includes any substance that could cause allergies.

Regulation (EC) No 648/2004 of the European Parliament and of the Council of 31 March 2004 on detergents.

Stockholm Convention on persistent organic pollutants (POPs)

The Stockholm Convention on persistent organic pollutants (POPs) forms a framework, based on the precautionary principle, which seeks to guarantee the safe elimination of these substances, which are harmful to human health and the environment, as well as reductions in their production and use. The Convention covers 12 priority POPs, although the eventual long-term objective is to cover other substances.

Council Decision 2006/507/EC of 14 October 2004 concerning the conclusion, on behalf of the European Community, of the Stockholm Convention on Persistent Organic Pollutants.

Agricultural nitrates

Council Directive 91/676/EEC aims to protect waters against pollution caused by nitrates from agricultural sources through a number of measures incumbent on Member States. These measures concern monitoring surface waters and groundwater, designating vulnerable zones, introducing codes of good agricultural practice, adopting action programmes, and evaluating the actions implemented.

Council Directive 91/676/EEC of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources.

Community strategy concerning mercury

In view of the risks mercury poses for human health and the environment, the European Union (EU) has drawn up a strategy based on six objectives, accompanied by specific actions, aimed mainly at reducing the quantity and the circulation of mercury within the EU and throughout the world as well as human exposure to this substance.

Communication from the Commission of 28 January 2005: “Community Strategy concerning Mercury”.

Protection of the aquatic environment against discharges of dangerous substances (until 2013)

The European Union (EU) lays down harmonised rules to protect the aquatic environment against the discharge of dangerous substances. The new regulations impose in particular the granting of an authorisation for certain pollutant discharges, emission limits for some chemicals and an improvement in the quality of waters under national jurisdiction. This Directive is repealed by the Framework Directive on water as from the end of 2013.

Directive 2006/11/EC of the European Parliament and of the Council of 15 February 2006 on pollution caused by certain dangerous substances discharged into the aquatic environment of the Community.

Other substances: protection of groundwater

This Directive prohibits or limits the discharge of certain dangerous substances into groundwater and establishes systematic monitoring of the quality of such water. It will be repealed by the Water Framework Directive as of 21 December 2013.

Council Directive 80/68/EEC of 17 December 1979 on the protection of groundwater against pollution caused by certain dangerous substances.

7.3 Useful links

- Summaries of EU legislation: Water protection and management

8 MISCELLANEOUS HYDROLOGY STUDIES

World Water Assessment Programme. 2003. Water for People, Water for Life: The United Nations World Water Development Report. UNESCO: Paris.

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Chapter

5

Erosion and Hydrological Restoration

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Chapter 5

Erosion and Hydrological Restoration

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1 Erosion and Hydrological Restoration

The Alps play a crucial role in accumulating and supplying water to the continent. Recognised as the 'water towers of Europe', these mountains host most of the headwaters of the Danube, Rhine, Po and Rhone rivers; as such as, they deliver vital ecosystem services both within and beyond the region, underpinning social and economic wellbeing in vast lowland areas.

Troublingly, the alpine climate has changed significantly during the past century, with temperatures increasing more than twice the global average. This makes alpine mountains especially vulnerable to changes in the hydrological cycle and decreases in snow and glacier cover, which are already happening. Global climate change threatens is altering the alpine hydrological system drastically. Projected changes in precipitation, snow-cover patterns and glacier storage will further alter runoff regimes, leading to more droughts in summer, floods and landslides in winter and higher inter-annual variability.

Climate change may worsen current water resource issues and lead to increased risk of conflicts between users in the alpine region (particularly the south) but also outside the Alps where droughts are also expected to become more frequent. Observed and projected reductions in permafrost are also expected to increase natural hazards and damage to high altitude infrastructure. According to this, what will happen in drier climates such as the Mediterranean where these effects can be multiplied?

First let's take a data series that put the world scene today. The 27% of the land surface corresponds to mountain regions, being present in all continents. It is estimated that 10% of the world's population lives on the top of mountains, while 40% occupies the adjacent of the middle and lower basins (FAO, 2000). Consequently, half of the world's population depends directly or indirectly, on the resources and the social and ecological stability of mountain ecosystems and their watersheds.

The Ministerial Conference on the Protection of Forests in Europe (MCPFE) is the high level forest policy process, addressing all dimensions of sustainable forest management (SFM) in the pan-European region. MCPFE involves 44 countries of the European continent, the European Community and 41observer countries and international organisations (see: http://www. mcpfe.org). The concept of SFM was firstly defined by the MCPFE in the Resolution H1 of the Helsinki Conference (1993) as: 'the stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality and their potential to fulfil, now and in the future, relevant ecological, economic and social functions, at local, national, and global levels, and that does not cause damage to other ecosystems'. Such a concept has been recognised to be consistent with the application of the Ecosystem Approach to forest ecosystems in the pan-European region (MCPFE/PEBLDS, 2006).

The Global Forest Resources Assessment 2010 (FRA 2010) was aimed by FAO member countries during the eighteenth session of the FAO Committee on Forestry (COFO) in March 2007 (FAO, 2007). It is the most comprehensive assessment to date, both in terms of content and contributors. More than 900 people have been involved in the country reporting process alone, including 178 national correspondents and their teams, an advisory group, international experts, FAO staff, consultants and volunteers from around the world.

In this report appear the world´s forest map (Figure 1) and the statistics for regions and subregions used in FRA (2010) and its distribution.

The global distribution of forests can be seen in numerous publications globally or locally (Figures 2 and 3) and appears as green stains focus forest cover worldwide like the Amazon, large parts of Central Africa and the East Asia

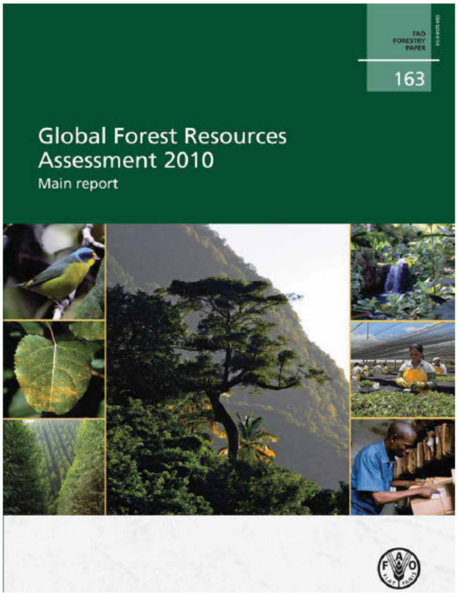

Figure 1. *Report of Global Forest Resources Assesment 2010. Find more: http://www.fao.org/forestry/fra/fra2010/en/*

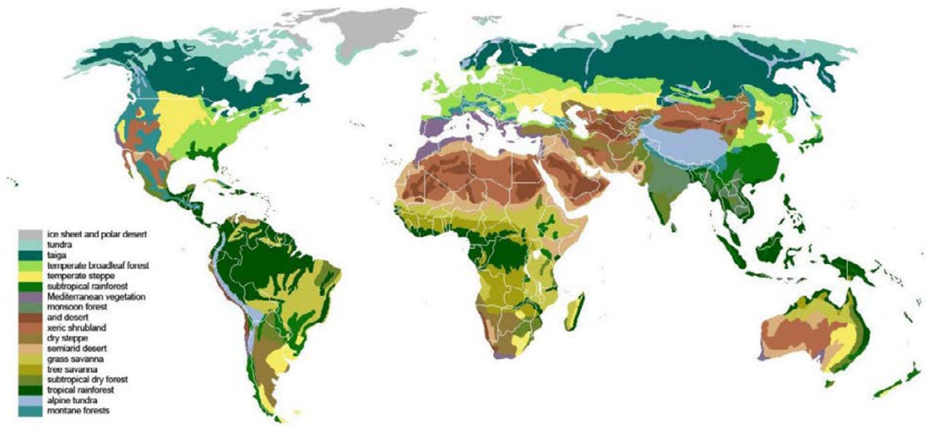

Figure 2. *World biomes are based upon the type of dominant plant (From Plant Ecology, 2011).*

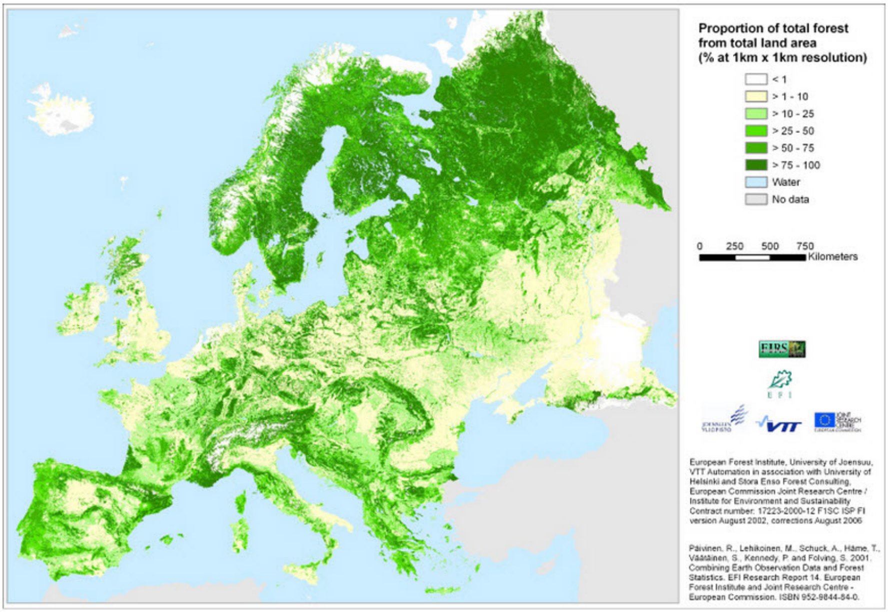

Figure 3. *Distribution of Forest in Europe (from European Forest Institute, 2011)*

The Figures 4 and 5 show the statistics displayed in the FRA report (2010). It is very useful to compare existing forest population and size in different parts of the world.

Region/subregion	Number of countries and areas	Land area (million hectares)	Population 2008			
			Total (million)	Annual growth rate (%)	Density (population/ km²)	Rural (% of total)
Eastern and Southern Africa	23	1 000	368	2.4	37	69
Northern Africa	8	941	209	1.7	22	49
Western and Central Africa	26	1 033	410	2.6	40	59
Total Africa	**57**	**2 974**	**987**	**2.3**	**33**	**61**
East Asia	5	1 158	1 547	0.5	134	53
South and Southeast Asia	18	847	2 144	1.4	253	66
Western and Central Asia	25	1 086	385	1.8	35	40
Total Asia	**48**	**3 091**	**4 075**	**1.1**	**132**	**59**
Total Europe	**50**	**2 215**	**732**	**0.1**	**33**	**28**
Caribbean	27	23	42	0.8	182	34
Central America	7	51	41	1.7	80	45
North America	5	2 061	454	1.0	22	19
Total North and Central America	**39**	**2 135**	**536**	**1.0**	**25**	**23**
Total Oceania	**25**	**849**	**35**	**1.3**	**4**	**30**
Total South America	**14**	**1 746**	**385**	**1.2**	**22**	**17**
World	**233**	**13 011**	**6 751**	**1.2**	**52**	**50**

Figure 4. Key statistics for regions and sub-regions used in 2010 (From: FAO 2010)

Distribution of forests by region and subregion, 2010

Region/subregion	Forest area	
	1 000 ha	% of total forest area
Eastern and Southern Africa	267 517	7
Northern Africa	78 814	2
Western and Central Africa	328 088	8
Total Africa	**674 419**	**17**
East Asia	254 626	6
South and Southeast Asia	294 373	7
Western and Central Asia	43 513	1
Total Asia	**592 512**	**15**
Russian Federation	809 090	20
Europe excl. Russian Federation	195 911	5
Total Europe	**1 005 001**	**25**
Caribbean	6 933	0
Central America	19 499	0
North America	678 961	17
Total North and Central America	**705 393**	**17**
Total Oceania	**191 384**	**5**
Total South America	**864 351**	**21**
World	**4 033 060**	**100**

Figure 5. *Distribution of forest by region and subregion, 2010 (From: FAO 2010)*

Table 1. Impacts and consequences of climate change on forest growth and forest conditions. (Source: EEA 2013a).

Climate effects	Impacts	Consequences
Increased CO_2 concentrations, longer growing season	Increased productivity of some species, e.g. for biomass production	Increased timber supply
Reduced snowfall	Decrease in snow damage Increase in wet snow damages	
Increase in average winter temperature	Winter chilling requirements for flowering and seed germination not met, incomplete winter hardening Reduction in winter cold damage Reduction in cold-associated mortality of insect pest, deer populations Potential for range of new species	Reduced natural regeneration Serious winter tree damage Increased tree damages
Higher earlier spring temperatures	Earlier budburst and potentially increased damages by late frosts	Reduced high-quality timber supply
Decrease in spring and summer rainfall	Drought during tree growth period Threat to newly planted trees Increase in forest fires Limiting current tree species range	Reduced tree growth, serious damage to trees Tree damage; increased tree vulnerability to insect attack; increased risk of soil erosion Changes in tree composition and thus in the range of goods and services
Increased winter rainfall	Waterlogging of soils, killing of tree roots	Reduction of rooting depths Increased vulnerability to droughts and storms
Reduced soil moisture	Changes in species suitability	
Increased frequency of high or extreme temperature episodes	Damaging effects of pests	Tree damage and mortality: loss of timber quality and quantity
Changes in temperature, rainfall and frequency of extreme weather events	Loss of biodiversity	Loss of biodiversity and habitats
Increase in storm events	Wind throws	Loss of quality timber supply, of recreational areas, gaps favouring regeneration
Droughts	Serious damages to trees and stands	Reduced timber volume and reduced high-quality timber supply; higher susceptibility to pests and pathogens; higher mortality; effects on nutrient cycling, habitats and fauna
Extreme weather events	Migration of tree species/loss of native tree species Potential reduction of some of the damaging effects of pests	Loss of biodiversity and habitats Reduced tree damage and yield losses (either quantity or quality)

In 2008, the total population in Europe was 732 million; 1 million from those were living over forest areas (Russia Federation excluded). This means that much of the population lives in mountain areas. In Italy, Greece, Austria, Portugal and Spain the mountain represents more than 50% of its surface. For example in Spain, 57.7% of the territory is located over 600 m and 18.45% is greater altitudes.

Water is one of the more evident socio-environmental dependence on a mountain ecosystem. The importance of the contribution from mountain areas to global water resources is absolutely crucial, as have shown different studies as Viviroli et al (2003) stating that 63% of the annual water contribution of 19 large basins on 4 continents was produced in mountain areas, although these areas only accounted for 32% of the basins. Consequently the specific discharge (flow per unit area) of mountain areas quadrupled the lowland areas. The hydrological regime of Mountains Rivers is markedly seasonal, mostly due to snowmelt or glacial, which leads to the natural regulation of runoff to defer the response to winter precipitation in spring and summer. This regulatory effect has greater weight in regions of arid and semiarid climate in wet weather. In some basins the first type of arid climate during certain months of the year almost all of the water flowing through their courses in their areas of plain has its source in the mountains.

Figure 6. *Albuñol ravine. Spain (Source: http://sciunt.files.wordpress.com/2010/09/147039-la-rabita-la-rabita.jpg).*

The sediment flux emitted by the ocean basins also reflects the preponderance of mountain environments on the plain, as set Milliman and Syvitki (1992) analyzed 280 rivers on several continents and find that 80% of the annual sediment load is originates in the mountain area from basins that not exceed 20% of its total area.

Water erosion and restoration of soils have been joined from the beginning of time. Different civilizations needed to produce their crops and planting trees. The various techniques that today continue to be implemented are an evolution of the old soil conservation practices on hillsides whose main objective was to use the ground and keep it.

It was not until the early twentieth century when a culture of Restoration was created through the concern of forest engineers. They became aware of the large amount of sediment that was issued to the drainage network of the basin where they were. In the mainly English-speaking world can associate this philosophy to the Watershed Management, a term that includes not only the technical aspects but is holistically integrating socioeconomic aspects of great value in developing countries.

1.1 The origin of the Forest-Hydrologic Restoration Plan (RHF).

This is one of the techniques used in Spain and therefore, well known in Latin America's. It all started with a correction work in mountain streams and their watersheds in the late nineteenth century. By then, deforestation had reached an alarming situation in Europe and in some mountain areas in Spain, especially in the Pyrenees. The roads became impassable and dangerous means by avalanches. The numerous natural phenomena of snow avalanches were happening in many Pyrenean valleys. This meant roadblocks, broken bridges, damage to coastal villages, hydroelectric facilities, etc...

In the Mediterranean region is also happening torrential episodes, mostly linked to the phenomenon known as "cold drop", causing flooding and silting with consequent effects on human and material losses.

As an example, the first Spanish law that emerged related slopes performances dates back to July 11, 1877, which established the Reforestation and Improving Public Forest as a legal instrument to prevent strong denudation of soils in situations of need for protection. This first law followed the enactment of the two R. D. 1888 and

1901, to restore degraded and treeless mountains. The first established a "watershed headwaters systematic restocking Plan", a task that was entrusted to the Corps of Engineers later the Forest Hydrological Services.

In science, it is possible that one of the most influential publications among engineers in southern Europe was that of E. Thiery: "Restauration des montagnes, Reboisement Corrections et des torrent" (1891). This book devotes a large part the need to combine the correction waterworks torrential channels with restoring their watersheds feeder, for the second proposed afforestation thereof. His famous statement among engineers pioneered the restoration of mountains: *You can´t fix a torrent, if together, or better previously, has not restored its feeder basin*.

In the corrector scheme a mountain watershed, which has just been described, vegetation as mountain forest is essential. It stands for stabilizing element of the basin before torrential mechanisms; it contributes both to increase infiltration as to decrease the speed of the sheet runoff and also favors the subsurface flow of water during periods of heavy rainfall. In resume, the forest is the quintessential natural regulator of water resources. These aspects must be added his great ability to defend the soil against erosion phenomena, both the impact of raindrops on the ground, as derivatives crawl disaggregated soil particles by runoff flows.

Around 1940 extends the use of the methodological tool of RHF in the Spanish basins due to the development of the Watershed Restoration Program-Forest, adapting to this technique that had already been tried with good results in the correction of mountain torrents.

In mountain areas or basins header reservoirs where there were problems requiring classic torrent control measures, it was logical that they be implemented as such. But large areas of these basins were primarily agricultural and other, that her earrings should not be, was at that time cultivated, in most cases without any soil conservation measure. The transformation of such agricultural uses are based on the Management of the uses, is what would be called Agro-hydrological management at the end of the Land Use, all pre Hydrological Restoration Project-Forest. The reforestation of these lands to agricultural use with slopes greater than 30% and low scrub of equal slopes was carried out under projects RHF.

At that time the first classifications were published agrologic land in the United States (Bennett, 1939), which limited land for the cultivation of which were permanent covered book.

As we have seen in the preceding paragraphs, the weight of land use is very important within the RHF in a watershed (Fig. 7). This has led in many cases it has come to distort the original concept and inclusive of restoration of mountain watersheds. However, we should mention that the repopulation of the land on steep slopes, not only helps to reduce water erosion in them, but also improves hydrological conditions.

The general goals in the RHF are the follows:

- The erosion control. Retention by controlling soil erosion, while trying to take advantage of this resource.
- The regulation of floods and flow generated
- Water redistribution

The formal aspect is of engineering projects, which has been adapted and improved over time, with new tools such as GIS and Remote Sensing which has yielded new results closer to reality and more performances maps accurate. This description will provide the second major objective of all RHF, the Agro-hydrological Management of the basin section included within the project, regardless of that goal. The project must describe, justify and calculate the work and the work carried out in compliance with the draft RHF mentioned in accordance with an action plan to be included therein. Finally, we evaluate the costs and draw the necessary budgets for the implementation of the actions and the work entered in the project according to the established work schedule.

Therefore, the project can be summarized in the following steps:

1. Basin Study in order to obtain all information describing the basin level fundamental factors such as climate, soil, vegetation and topography.

2. Knowing how to behave different basin rainfall events, either real or simulated, to estimate or predict the effects or that can be expected of them.

3. Schedule a Planning agro-hydrological response of the basin especially their physical capabilities and objectives to be with the project.

4. Describe, justify and calculate the projected works and basin RHF. In addition to establishing a timetable for the completion of the above actions and work.

5. Evaluate the costs and prepare budgets necessary for the execution of the works and in the proposed work.

1.2 Agro-hydrological Planning.

It focuses primarily on the watershed and agronomic intended to regulate land use according to their hydrological behavior taken into account hydrological models, soil conservation and land use. It takes into account hydrological models, soil conservation and land use. An agro-hydrological planning must be based on at least the following factors set out for them from a classification of restorative actions that are required to perform in each of the different areas of the watershed restoration object (Table 2).

Table 2. The different parameters of the watershed restoration object.

Altitudes as watershed areas	Areas dominants (headwaters)
	Areas dominated (valleys)
Cover class level	The current state of the vegetation.
	Provenance
	Land use in accordance with suitability
Morphology	Slopes
	Orientation
Geology	Areas with soil erosion
	Areas with piping erosion
Soil Science	Types of soil in different areas of watershed
Protection models of soil	Index of protection soil by vegetation
	Parametric erosion models (USLE; RUSLE)
	Another erosion models (WEPP;EUROSEM;...)
Phytosociologic Index	Bioclimatic Index
	Potential Index

Actions in the territory	In the hillslope
	In the channel
Classification of project area	Action zones
	Recommended zones
	Zones without actions

1.3 RHF Action Planning

To achieve the objectives set out in the draft RHF the next types of actions should be follow:

a) Actions in hillslopes focus on the creation, control and improvement of permanent vegetative cover; constitutes forest restoration, and its main job is Reforestation. These involve:

1. Soil preparation techniques for reforestation
2. Selection of species
3. Polygons of action and forest stands
4. Proposed Measurements

From these four sections, the first should ensure a suitable ground to allow the initial development of the plants into the soil with restocking; has a mechanical-hydraulic important content. The second should serve the temperament (auto-ecology) of the species and quality assurance of the plant contain both research fields and very important. Finally, the third and fourth correspond basically to the technical specifications of the project.

b) Actions in channels. These actions entail design and implementation of hydraulic correction torrential channels, which requires:

- Choice of appropriate structures
- Design and calculation of the structures adopted

- Measurements

In many European countries with major mountain systems as Pyrenees; Alps or Carpathians have developed numerous structures such as check dams retention and consolidation.

Figure 7. *Check dam in the Carpatian area. (From: García J.L.)*

1.4 Complementary actions

The most important are: the construction of a road transport network in order to access to different areas of work and as a means of escape from forest fires, the various stages of water drains in roads and other points of interest.

1.5 Watershed restoration and climate change

This section seeks to provide an historical review of Watershed Management; an introduction on how climate change will impact in watershed management; will make several observations and recommendations about flood control, erosion control, storm water management, and land management; and will address the types of adaptation strategies necessary for successful Watershed Management in a future changing climate.

Watershed Management is the practice of managing natural resources on the basis of a physiographic Watershed boundary, began in the world following World War II. Since then, its definition has expanded: first from a focus on flood control and erosion to one which includes broader terrestrial and aquatic environments, and more recently to include social issues related to the use of the natural environment, making watershed management one of the most inclusive ecosystem-based management frameworks, developed to date. Now, it must open and expand again to address Climate Change, and must do so with respect to natural science, mitigation, and adaptation, terms which will be explained in more detail below.

Figure 8. *Carpatian forest road. (From: García J.L.)*

In the 1970's, it was recognized that urban land forms removed permeable areas and replaced them with impermeable surfaces, thus generating a higher volume of water. This is common in all urban areas to large cities worldwide. This increase in volume was being characterized as increasing surface runoff, less evapotranspiration, less surface depression storage and therefore less infiltration. The overall consequences of this land form change have been increased flooding and erosion along receiving streams.

In addition, water quality has been degraded to the point that many streams now support a significantly different, or much reduced fishery. The change in the aquatic environments has now begun to affect both the flora and fauna that exists within our valley systems. While new initiatives have been introduced that attempt to reduce the impacts on the natural systems through development, changes continue to occur as a consequence of past and current actions.

Current initiatives and strategies of Watershed Management hinge on working in concert with the dynamic aspects of the natural environment and its features. An example of this (Haley, D. 2000) would include managing the watercourses based upon their valley and stream corridors to allow for the natural process of meandering streams as a component of a larger conveyance feature. This management strategy allows for the evolution of the system through sediment transport issues such as erosion and deposition along a reach of stream. The development of strategies related to natural heritage features on a watershed also allow for an integration of flexibility and evolution within the system. As such, the concept of management on a watershed is based to some degree on the ability to manage and plan within the system, while allowing natural processes and changes to continue to take place. The watershed and its current management objectives, therefore, inherently allow for some degree of adaptation related to the potential impacts of climate change.

Climate change will bring changes to the atmospheric components of the cycle. Changes in evaporation rates, severity of storms, increased temperatures and droughts created through climate changes may result in significant alterations within the natural ecosystem of a watershed.

1.6 Watershed Management Issues

Given the nature of the changes which are likely as a result of climate change, it can be expected impacts in virtually all aspects of the strategies and procedures currently in place for managing watersheds. For the sake of clarity, some of the key categories and some of the potential impacts are outlined below.

1.6.1 Flood Control

A change in meteorological inputs will result in changes within the hydrologic flow regime of a watershed. Typical flooding impacts will result from more severe weather giving more intense rainfalls at an altered frequency of occurrence. Additional changes would be an increased number of mid-winter melts as a consequence of warmer winter temperatures. These changes will have varying impacts on individual watersheds and watercourses. Those watercourses sensitive to thunderstorm type flooding may experience more frequent and extensive flooding problems. Watersheds which typically are only impacted by spring snow melt flooding may have a reduced flood risk due to mid-winter snow pack losses or may have risks shifted earlier into the winter period. Changes in the melt of snowpack's, such as earlier snowmelt runoff events may also impact other Water Management issues such as reservoir operations.

Similar to the issue of flood impacts, a change in intensities and susceptibility to severe thunderstorm type events will tend to reduce the effectiveness of flood warning. These intense storms tend to occur with shorter lead times. In addition, with the shift to more intense storms, will come the increase in urban flood issues such as storm sewer surcharging, street flooding and basement flooding. In areas with combined storm and sanitary services, overflows may become more commonplace.

The issue of not only more sever and frequent thunderstorm type events may be compounded by the likelihood of more severe and frequent major tropical storms in different parts of the world. The implementation of hydrological actions that include the expansion of the floodplain or river free space can get prevent major disasters

1.6.2 Erosion Control

Watershed Management strategies also have been developed on erosion processes within the basin. Erosion is a natural process related to the fluvial geomorphology of the watercourse. A stable system tends to reflect a balance between erosion and deposition along the watercourse reaches. As noted previously, urbanization has resulted in changes to these processes through changes in the flow regime or the flow conveyance system. Additional changes as a result of climate change will tend to create erosion within stable watersheds and further increase erosion problems within watercourses currently undergoing changes. The low flow channel of a stable river/stream system reflects the need of the conveyance feature related to the bank full flow need within the watershed. The return period associated with the bankfull, or channel forming flow, is typically defined to be at or near the 1.5 year flow rate. Should climate change lead to increases in the frequency of severe storms and in the frequency of the channel forming flows, it can be expected that much more rivers and streams will react to reflect the changes at this flow rate.

An additional area of concern related to erosion centres on a potential increase in freeze / thaw along the stream banks as a consequence of a change in mid-winter melt events. An increase in these events will tend to cause structural failures within the banks, further destabilizing them, increasing mass movements and surface erosion.

1.6.3 Stormwater Management

Stormwater management reflects a program specifically designed to mitigate impacts related to changes within the hydrologic cycle especially due to urbanization. This program has also evolved from one related to flood and erosion control to one which attempts to deal with issues of both water quantity and quality.

Existing facilities will no longer be in position to provide the levels of quality or quantity control they presently provide, and may in some instances be at risk of failure.

1.6.4 Land Management

Watershed Management programs and policies also encompass terrestrial habitats as well as aquatic. Identifying Environmentally Significant features, such as forest blocks, wetlands, valley and stream corridors, and developing policies or procedures to protect and enhance these features is a major component of management strategies.

These features contain functions related to the flora and fauna within them, provide a social function for the residents of the watershed, and provide benefits related to the hydrologic cycle.

Changes within the climate will result in significant impacts and changes within these features as well. The increase in temperatures will extend growing seasons and allow for additional plant species to enter the watershed, many of which could very well be invasive and force changes in the existing biodiversity.

The changes in temperature may also allow for a movement of additional animal and bird species into the watershed or the movement out of or extinction of existing species. Changes in meteorological inputs such as extended drought periods will also create stress within the flora and fauna, resulting in changes such as population reductions in some species or the eventual replacement with species of flora and fauna more resistant to these types of climate changes.

Watershed Management strategies inherently reflect policies and programs with a degree of flexibility or dynamism as they are designed to deal with natural systems and processes which are constantly undergoing change. As such, many of the strategies also provide a basis to evolve to include the flexibility to deal with changes in the natural and atmospheric systems brought about through climate change. The following represent areas where change in policies or programs can and will be necessary if Watershed Management is to continue as a viable ecosystem based management structure.

1.6.5 Surface Hydrology

Modelling of the surface hydrology within a watershed should be updated to allow for impacts of climate change to be analysed. Models based upon a continuous flow simulation, and based upon a water budget approach, will allow for a series of climate variations and their impacts to be reviewed and sensitivities and trends of potential impacts identified. Once completed, regulatory flood standards will be assessed, revised bank full flow estimates defined, and strategies developed to address these flow changes. Policies and procedures need to be developed to deal with the changes in the fluvial components of a watercourse, such as erosion, and meander belt movements to allow for revised channel design standards, and remediation. Planning related to impacted infrastructure such as bridges, culverts, sewers, and outfall structures, needs to be addressed. Flood risk planning and remedial works associated with minimizing future flood vulnerabilities can be identified, prioritized, and undertaken as required. Operational viability of existing flood control structures can be assessed, and operational modes revised to account for a revised flow regime, as detailed climate change assessments are developed.

1.6.6 Aquatic Environment

Fisheries management plans will be revised and updated to reflect the most effective way of dealing with climate change impacts through identification of resources which will be sensitive to climate impacts. The management plans will then reflect how these resources could then be protected, enhanced or managed to reflect the long term habitat and species changes.

1.6.7 Ground Environment

Ground natural heritage strategies will include policies and programs which allow both the adaptation of planting, restoration, and management plans to reflect climate change and also to allow for the mitigated aspect of the terrestrial environment as a carbon sink to assist in reducing greenhouse gasses in the atmosphere.

1.7 Climate Change Science Needs

To define the impacts of climate change at a level of detail where effective adaptation can be incorporated into Watershed Management, a great deal of additional study and information will be required. Several areas of additional need are:

- A much more defined assessment of climate impacts on a watershed or a regional scale is required to facilitate any form of modelling and assessment.
- Climate projection improvements should be an assessment of storm frequency change as the typical design approach of looking back to plan forward will likely not remain as a functional tool.
- Studies to look at evaporation changes and their potential impacts to lake and reservoirs levels, droughts and the terrestrial environment.

The impacts and resultant changes that are anticipated from climate change on all the natural features and processes presently managed on a watershed basis will be occur over a time frame stretching into the second half of this century. Watershed Management plans are documents which incorporate policies, strategies, and programs designed to manage natural processes over an extended time frame, and as such, provides the ideal platform, and set of tools to allows for adapting to climate change.

2 Design of techniques for water erosion control

According to FAO, Watershed management is the process of formulating and carrying out a course of action involving the manipulation of resources in a watershed to provide goods and services without adversely affecting the soil and water base. Usually, watershed management must consider the social, economic and institutional factors operating within and outside the watershed area.

In order to clarify the concepts and the focus of this public action, this box defines and discusses two important terms:

2.1 Forest hydrology and watershed management

A watershed is a geographical area which is drained by a water course. Watershed management encompasses any human action aimed at ensuring a sustainable use of watershed resources.

Watershed management considers the management and conservation of all available natural resources in a comprehensive way. It establishes the link between natural resources management, agricultural production and livelihoods. It provides a framework to organize different land uses (forestry, pasture, agriculture) in an integrated way and by following a landscape approach. Watershed management involves the local population, politicians and technicians in decision-making processes. Although watershed management is space-bound, geographically circumscribed and mostly applied to upland and mountain areas, it is conceptually very broad

Forest hydrology is a discipline that deals with the interactions between forests and the water cycle. Forest hydrology provides useful information for the much-needed efforts to maintain and restore water-related ecosystems.

Forest hydrology is thematically and conceptually narrower than watershed management. It focuses mainly on the physical interactions between forests and water. However, forest hydrology covers a much broader geographical scope since it can apply to contexts which go beyond watersheds, such as swamp forests, riparian buffer zones or forests on saline-susceptible soils.

The Forest Hydrology is can be considerate as "special branch of Hydrology that studies the relation between water and soil, inside of framework that form woodlands or mountains" (López Cadenas de Llano, 1988 and 1994)

The great experience accumulated in Europe throughout this last century has been fundamental in consideration this branch of classic Hydrology. It use common technics but theirs aims are different. Is supported in numerous congress and internationals meetings that has formed this special branch

Table 3 shows a summary of actions for the control of a torrential river and by extension in a Watershed degraded has problems both on the slopes and in their channels. Table includes a series of techniques that can be implemented in each of these areas. The photos accompanying this text were taken at different sites that have worked in Watershed Restoration for different reasons as acting post fire, landslides, and the implementation of agroforestry techniques, retention and consolidation of sediments watercourses, the flood control from the head of the basin, fighting avalanches.

Figure 9. *Check dam in Canary Island. (From: Profoyma 2005)*

Figure 10. *Living Fascines in Chiapas (México). Works of CONAGUA in Lacandona Hill. (From: García J.L.)*

Table 3. Summary of actions for the control of a torrential river

<table>
<tr><th colspan="4">Actions</th><th>Goals</th></tr>
<tr><td rowspan="8">Hillslopes</td><td colspan="2">Forestation</td><td></td><td>Control of sheet, rills and gullies</td></tr>
<tr><td rowspan="3">Biological actions</td><td rowspan="2">Reforestation</td><td rowspan="2"></td><td>Improvement infiltration and hydric regulation</td></tr>
<tr><td>Runoff control</td></tr>
<tr><td>Terraces</td><td></td><td>Control of sheet and rill erosion</td></tr>
<tr><td rowspan="3">Mechanics practices</td><td rowspan="2">Stips</td><td rowspan="2"></td><td>Soil moisture control</td></tr>
<tr><td>Mass movements control</td></tr>
<tr><td>Dry masonry (Albarradas)</td><td></td><td>Gullies control</td></tr>
<tr><td>Small transverse structures</td><td>Fascines</td><td></td><td>Headwater erosion control</td></tr>
<tr><td rowspan="7">Torrencial Channel (F>1)</td><td rowspan="5">Erosion zone (headwater)</td><td rowspan="5">Transverse structures</td><td rowspan="2">Consolidation check-dams</td><td>Consolidation of unstable hillslopes (landslides)</td></tr>
<tr><td>Equilibrium profile in bed</td></tr>
<tr><td rowspan="2">Retention check-dams (total or selective)</td><td>Partial retention of sediments</td></tr>
<tr><td>Defence of villages, gates, hydropower centrals...</td></tr>
<tr><td>Small waterwheel</td><td rowspan="3">Erosion control in bed</td></tr>
<tr><td rowspan="2">Deposition zone (dejection cone)</td><td>Longitudinal structures</td><td>Breakwater, groynes, walls, bioengineering technics...</td></tr>
<tr><td>Mixed structures</td><td>Step profile with erosionables reachs</td></tr>
<tr><td rowspan="2">Fluvial Channel (F<1)</td><td rowspan="2">Rivers Medium and low reaches</td><td rowspan="2">Longitudinal structures</td><td rowspan="2">Breakwater, groynes, walls, bioengineering technics...</td><td>Defence and protection of banks against laterals erosions</td></tr>
<tr><td>Defence against floods and fluvial geomorphologic rectify</td></tr>
</table>

Figure 11. Living Wall in Lacandona Hill (Chiapas, Mexico). (From: García J.L.)

Figure 12. *Living Wall in Lacandona Hill (Chiapas, Mexico) in a ravine. (From: García J.L.)*

Figure 13. *Gabion Check dam built from native species in Chiapas. (From: García J.L.)*

Figure 14. CONAGUA training in native species in Chiapas. *(From: García J.L.)*

Figure 15. *Gabion Check dam built (albarrada) in Mediterranean region. (From: García J.L.)*

Figure 16. Masonry Check dam built in Mediterranean region. (From: García J.L.)

Some examples in Spain show the Restoration in watersheds after more than 100 years The Arratiecho ravine is placed in the Gallego river basin and the sequence of pictures

Figure 17. Arratiecho ravine in 1902 (Source: Spanish Forest photographic library)

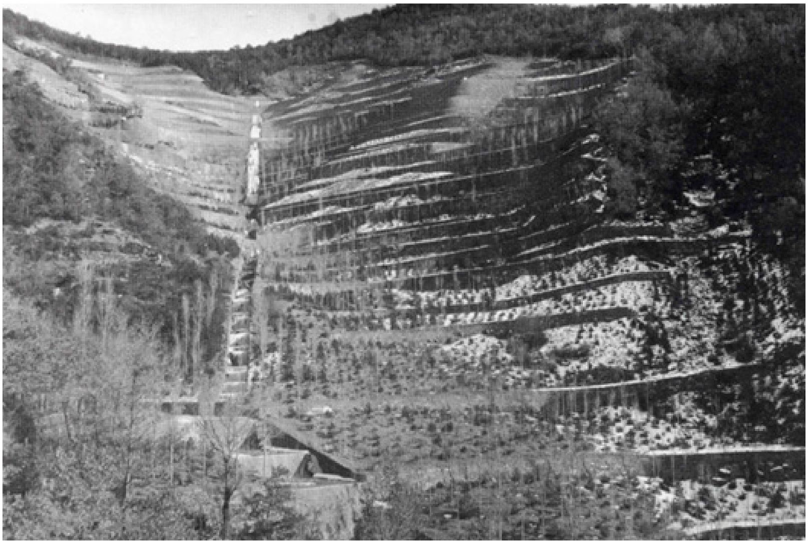

Figure18. *Arratiecho ravine after the first restoration work with retaining walls and slopes reforestation in 1910 (Source: Spanish Forest photographic library)*

Figure 19. Arratiecho ravine walls in 2005 (From: García J.L.)

Figure 20. The outlet channel of Arratiecho ravine in 2005 (From: García J.L.)

Figure 21. *Spanish Forest Service has built numerous check dam in mountain rivers with different designs and materials (From: García J.L.)*

Figure 22. *Check dam in Aras ravine (From: García J.L.)*

Figure 23. Structures stabilising the level of the stream bed in Arás ravine (From: García J.L.)

Figure 24. *Consolidation check dam in Guarga de Cajol (Huesca) in Pyrenean area (From: García J.L.)*

Figure 25. *Concrete check dam in Remascaro ravine (Huesca) in Pyrenean area (From: García J.L.)*

3 Adaptation to climate change improving water distribution by land slope techniques

Climate change will very likely have an important adverse impact on the availability and quality of water in many regions of the world. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2012) forecasted considerable changes in the amount, the temporal and the spatial variation of precipitation in every region.

Forests themselves are vulnerable to climate change. Reduced and more erratic rainfall and runoff will influence the vitality, resilience and even survival of trees and forest ecosystems. Action needs to be taken to reduce the vulnerability of forests and enhance their resilience to climate change with the aim of ensuring the continued provision of vital ecosystem services and protective functions ensured by forests.

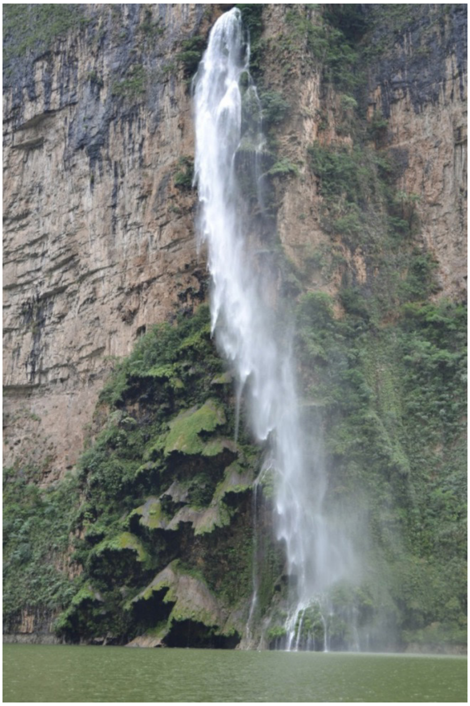

Figure 26. *The terrifying Cañon del Sumidero, a deeply carved canyon not far from Tuxtla Gutíerrez (Mexico).* (From: García J.L.)

These adaptation measures need to be consistent with sustainable forest management principles and practices based on improved knowledge of the functioning of forest ecosystems. Sustainable management of forests requires continuous efforts, financial resources and political commitment. One constraint to halting and reversing global forest loss is the fact that those who manage forests receive little or no compensation for the services (i.e. water) they provide. Funds should be made available through incentives, transfer-payments, subsidies or Payments for Ecosystem Services (PES) to those who provide the ecosystem services (i.e. forest owners), by those who benefit from the services (i.e. water users). In fact, the linkage between forests and water can generate significant economic benefits. It is promising to see an increasing number of successful PES schemes under implementation in industrialized as well as in developing countries.

Despite significant advances in the scientific understanding of forest and water interaction, the role of forests in relation to the sustainable management of water resources remains a contentious issue. Difficulties persist in transferring research findings to different countries, regions or even watershed scale.

Furthermore, there is a gap between research and policy. This gap persists partly because of the difficulties involved in formulating general principles about forest and water interactions, and partly because of a failure to communicate effectively the results of hydrological and forestry research to policy-makers. Further education and capacity building across disciplines is necessary in order to address this problem.

Figure 27. *Conference of Deans and Directors in Brasov (2010) in a field research (From: García J.L., Brasov 2010)*

The numerous interactions and benefits between forest and water sectors highlight the need for strengthening existing and establishing new linkages between them, and fostering their collaboration. This cooperation is of particular importance as the forest and water sectors need to shape their responses to climate change, resulting in possible adjustments of relevant policies and legislations, institutional development, research reorientation and integrated management strategies and plans.

As mentioned above, in Europe appeared in early twentieth century a number of laws in the countries affected by a sudden change in their forest cover. The mountainous character central European countries such as France, Switzerland, Austria, Italy and Spain among others, seeking legal support with which to start proceedings on slopes and channels of river that could reverse the degrading environment had occurred. Thereafter the proceedings had a spectacular advance as you can see today in many river restored.

With climate change should happen the same, countries should adapt to the phenomenon and watershed restoration techniques must also adapt to it and be effective and efficient techniques and technologies adapted to the objectives.

Figure 28. *Nursery facility near Brasov, Romania (From: García J.L., 2010. Brasov)*

4 Flood Control in a changing climate

Floods, storms and other hydro-meteorological events account for around two thirds parts of the damage costs of natural disasters, and these costs have increased since 1980, according to a recent EEA assessment of climate change impacts in Europe.

The observed increase in damage costs from extreme weather events is mainly due to land use change, increases in population, economic wealth and human activities in hazard-prone areas and to better reporting. To confirm the exact role played by climate change in flooding trends in past decades, it would be necessary to have more reliable, long-time series data for rivers with a natural flow regime.

In any case, it is likely that rising temperatures in Europe will intensify the hydrological cycle, leading to more frequent and intense floods in many regions. Although quantitative projections for flood frequency and intensity are uncertain, the contribution of climate change to the damage costs from natural disasters is expected to increase in the future due to the projected increase in the intensity and frequency of extreme weather events in many regions.

Hans Bruyninckx, EEA Executive Director, said: "Considering flood risk in Europe, we can see climate change will be an increasingly important factor. But in many cases, flood risk is also the result of where, and how, we choose to live – increases in costs from flooding in recent decades can be partly attributed to more people living in flood-prone areas."

The report, 'Climate change, impacts and vulnerability in Europe 2012 http://www.eea.europa.eu/media/newsreleases/climate-change-evident-across-europe finds that higher average temperatures have been observed across Europe as well as decreasing precipitation in southern regions and increasing precipitation in northern Europe. The Greenland ice sheet, Arctic sea ice and many glaciers across Europe are melting, snow cover has decreased and most permafrost soils have warmed.

Extreme weather events such as heat waves, floods and droughts have caused rising damage costs across Europe in recent years. While more evidence is needed to discern the part played by climate change in this trend, growing human activity in hazard-prone areas has been a key factor. Future climate change is expected to add to this vulnerability, as extreme weather events are expected to become more intense and frequent. If European societies do not adapt, damage costs are expected to continue to rise, according to the report.

Some regions will be less able to adapt to climate change than others, in part due to economic disparities across Europe, the report says. The effects of climate change could deepen these inequalities.

Jacqueline McGlade, EEA Executive Director said: "Climate change is a reality around the world, and the extent and speed of change is becoming ever more evident. This means that every part of the economy, including households, needs to adapt as well as reduce emissions."

While precipitation is decreasing in southern regions, it is increasing in northern Europe, the report says. These trends are projected to continue. Climate change is projected to increase river flooding, particularly in northern Europe, as higher temperatures intensify the water cycle. However, it is difficult to discern the influence of climate change in flooding data records for the past.

Figure 29. *Research material used in some areas of a basin for predict changes and preview actions for protection. Carpatian station, Romania (from: Nita M. 2010)*

Figure 30. *Flow from tropical storms and hurricanes in Mexico (from: García J.L., 2011)*

Flood events can take many forms, including slow-onset riverine floods, rapid-onset (flash) floods, accumulation of rainwater in poorly-drained environments, and coastal floods caused by tidal and wave extremes. Both inland and coastal flooding may be associated with windstorm events. Floods also vary greatly in scale and impact, according to depth, velocity of flow, area covered, content, speed of onset, duration and seasonality. A flood event that has severe consequences (variously defined) may be termed a flood disaster, and the human impact of flood disasters is concentrated disproportionately in developing countries. Though major limitations remain in our ability to make robust projections of future rates of climate change and its effects, increasing predictive evidence of heightened global risk of inland and coastal flooding is emerging. Over the next 100 years, flooding is likely to become more common or more intense in many areas, especially in low-lying coastal sites and in areas that currently experience high rainfall. Marginal changes in the geographical distribution of flooding are also possible. However, it is not feasible to predict the precise locations at increased risk of flooding due to climate change: part of the problem is that flood risk dynamics have multiple social, technical and environmental drivers.

Flood events are the most frequently occurring natural disasters worldwide, and may increase in the future as a result of climate change.

4.1 The European Flood Alert System

Between 1998 and 2004, Europe suffered over 100 major damaging floods, including the catastrophic floods along the Danube and Elbe rivers in summer 2002. Severe floods in 2005 and 2007 further reinforced the need for concerted action. Since 1998 floods in Europe have caused some 700 deaths, the displacement of about half a million people and at least €25 billion in insured economic losses.

The Directive 2007/60/EC on the assessment and management of flood risks entered into force on 26 November, 2007. This Directive now requires Member States to assess if all water courses and coast lines that are at risk from flooding, to map the flood extent and assets and humans at risk in these areas and to take adequate and coordinated measures to reduce this flood risk.

Since the beginning of 2003 the European Commission DG Joint Research Centre (JRC) is developing a prototype of European Flood Alert System (EFAS) in close collaboration with relevant institutions in the Member States. The JRC benefits from experience gained already during the European Flood Forecasting System (EFFS) project financed by the EU DG Research.

The European Flood Alert System (EFAS) is a research project that aims at improving preparedness for oncoming flood events by:

- informing the authorities in the Member States of the possibility of a flood before the local systems capture the event with their own monitoring and forecasting systems;
- providing catchment based information that gives downstream authorities an overview of the current and forecasted flood situation also in upstream countries.

This does not only include the immediate upstream country but also any further potentially useful upstream information. EFAS provides medium-term (3 to 10 days) flood forecasts, based on different meteorological inputs, as complementary information to the typical short-term (less than 48 hours) forecasts performed by national centres. The challenge of EFAS is to combine all hydrographs, calculated from different medium-range weather forecasts, into one early flood warning information that is useful for local flood forecasting centres. EFAS forecasts are supposed to be used as a pre-alert to allow the receiving authorities to be aware of the possibility of a flood taking place. In other words, with EFAS forecasts in hand, local forecasters can already play through a number of different "what if" scenarios and, as the event approaches and its location and magnitude become more certain, national authorities can act more quickly and accurately, increasing the economic value of their forecasts.

Figure 31. *Example of a flooding map in Spain*

The key tool of Directive 2007/60 is the development of Risk Management Plans Flood, executed before December 2015, regulated in each European country.

Management plans will aim to achieve coordinated action by all levels of government and society to reduce the negative consequences of flooding based on the programs of measures that each government should apply in the scope of their powers to achieve the intended target.

Management plans set for each area Potential Significant Flood Risk management objectives of flood risk and shall, in accordance with each competent authority to perform actions. These actions may be specific or have a local or regional level or the entire watershed depending on the type of action. Each competent management will be responsible for the approval of its program of measures, establishing coordination mechanisms Plan.

Management Plans, which among other measures should be:

- River restoration measures and measures for hydrological-agroforestry watersheds.
- Measures to improve linear drainage infrastructure.
- Measures for flood prediction.
- Civil protection measures.
- Measures of Planning and Development.
- Measures considered promoting safe from flooding on people and property and, in particular, agricultural insurance.
- Structural measures raised and cost-benefit studies that justify and possible measures for controlled flooding of land.

These measures must be reconciled with those established with the Water Framework Directive, seeking the best possible environmental options for flood risk management, and according to the European Commission, "we must work with nature and not against it."

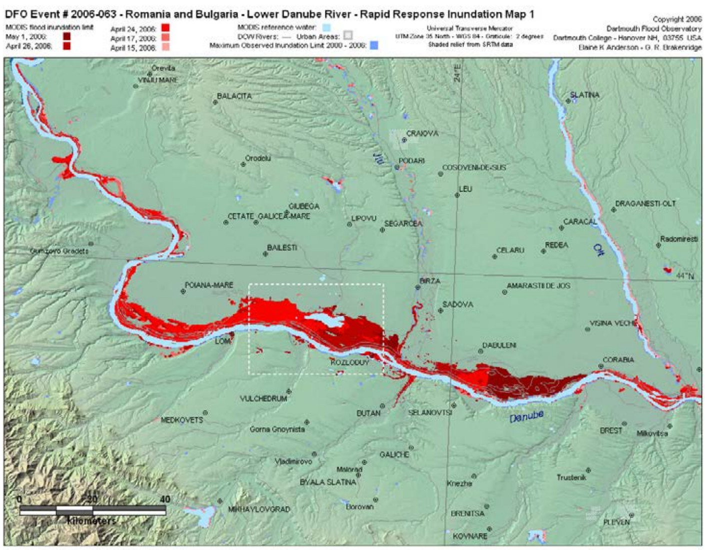

Figure 32. *From: DFO 2006-063; Flooding: 04/07/06 - ongoing as of 04/21/06; Romania and Bulgaria - Lower Danube River*

The EU Project (FLOODSite: Integrated Flood Risk Analysis and Management Methodologies) aims to deliver: (i) an integrated, European, methodology for flood risk analysis and management; (ii) consistency of approach to the causes, control and impacts of flooding from rivers, estuaries and the sea; (iii) techniques and knowledge to support integrated flood risk management; (iv) sustainable "pre-flood" measures (spatial planning, flood defence infrastructure and measures to reduce vulnerability); (v) flood event management (early warning, evacuation and emergency response); (vi) post-event activities (review and regeneration); (vii) dissemination of this knowledge and networking and integration with other EC national and international research.

The Dartmouth Flood Observatory detects, maps, and measures major flood events worldwide using satellite remote sensing. The record of such events is preserved as a "World Atlas of Flood Hazard". An Active Archive of Large Floods, 1985-2006, describes these events individually. Maps and images accompany many of the floods, and can be accessed by links in the yearly catalogues. As the archive of reliable data grows, it is increasingly possible to predict where and when major flooding will occur, and to analyse trends over time. "Surface Water Watch™" is a satellite-based surface water monitoring system. Orbital AMSR-E microwave measurements over selected river reaches are used to measure discharge and watershed runoff every two days. The system can be used to determine where flooding is under way, to predict inundation extents, and to assess the surface water status of seasonal wetlands.

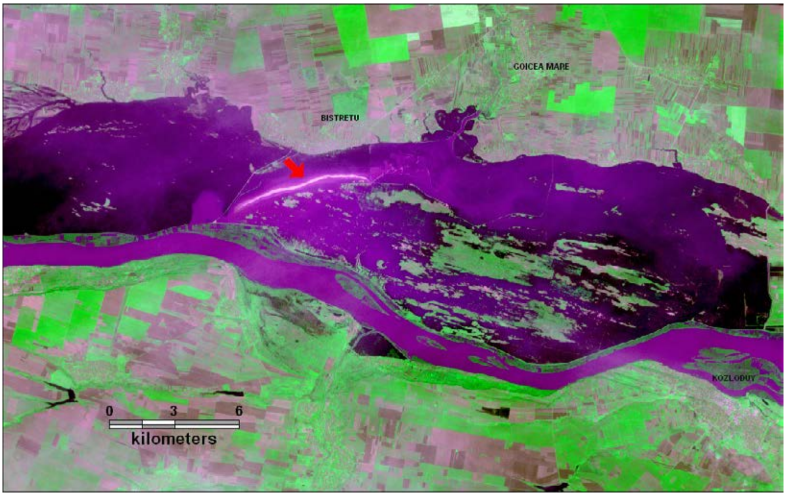

Figure 33. *From: DFO 2006-063; Flooding: 04/07/06 - ongoing as of 04/21/06; Romania and Bulgaria - Lower Danube River*

4.2 Mortality due to flood events.

Deaths associated with flood disasters are reported in the EM-DAT disaster events database. The most readily identified flood deaths are those that occur acutely from drowning or trauma, such as being hit by objects in fast-flowing waters. The number of such deaths is determined by the characteristics of the flood, including its speed of onset, depth, and extent. Information on risk factors for flood-related death remains limited, but men appear more at risk than women. Those drowning in their own homes are largely the elderly.

4.2.1 Appendix

Directive 2007/60/EC on the assessment and management of flood risks.

In the entire document it can see a lot of sections with references to floods and climate change.

(2) Floods are natural phenomena which cannot be prevented. However, some human activities (such as increasing human settlements and economic assets in floodplains and the reduction of the natural water retention by land use) and climate change contribute to an increase in the likelihood and adverse impacts of flood events.

(4) Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy (3) requires river basin management plans to be developed for each river basin district in order to achieve good ecological and chemical status, and it will contribute to mitigating the effects of floods. However, reducing the risk of floods is not one of the principal objectives of that Directive, nor does it take into account the future changes in the risk of flooding as a result of climate change.

(14) Flood risk management plans should focus on prevention, protection and preparedness. With a view to giving rivers more space, they should consider where possible the maintenance and/or restoration of floodplains, as well as measures to prevent and reduce damage to human health, the environment, cultural heritage and economic activity. The elements of flood risk management plans should be periodically reviewed and if necessary updated, taking into account the likely impacts of climate change on the occurrence of floods.

Figure 34. *Flood in Pakistan (http://granmogol.wordpress.com/2010/08/14/inundaciones/)*

Besides in the chapter II (PRELIMINARY FLOOD RISK ASSESSMENT) says:

Article 4

1. Member States shall, for each river basin district, or unit of management referred to in Article 3(2)(b), or the portion of an international river basin district lying within their territory, undertake a preliminary flood risk assessment in accordance with paragraph 2 of this Article.

2. Based on available or readily derivable information, such as records and studies on long term developments, in particular impacts of climate change on the occurrence of floods, a preliminary flood risk assessment shall be undertaken to provide an assessment of potential risks. The assessment shall include at least the following:

a) maps of the river basin district at the appropriate scale including the borders of the river basins, sub-basins and, where existing, coastal areas, showing topography and land use; (b) a description of the floods which have occurred in the past and which had significant adverse impacts on human health, the environment, cultural heritage and economic activity and for which the likelihood of similar future events is still relevant, including their flood extent and conveyance routes and an assessment of the adverse impacts they have entailed;

(c) a description of the significant floods which have occurred in the past, where significant adverse consequences of similar future events might be envisaged; and, depending on the specific needs of Member States, it shall include:

(d) an assessment of the potential adverse consequences of future floods for human health, the environment, cultural heritage and economic activity, taking into account as far as possible issues such as the topography, the position of watercourses and their general hydrological and geomorphological characteristics, including floodplains as natural retention areas, the effectiveness of existing manmade flood defence infrastructures, the position of populated areas, areas of economic activity and long-term developments including impacts of climate change on the occurrence of floods.

In the chapter VIII says in the Article 14 in the section 4 about the Climate Change

Article 14

1. The preliminary flood risk assessment, or the assessment and decisions referred to in Article 13(1), shall be reviewed, and if necessary updated, by 22 December 2018 and every six years thereafter.

2. The flood hazard maps and the flood risk maps shall be reviewed, and if necessary updated, by 22 December 2019 and every six years thereafter.

3. The flood risk management plan(s) shall be reviewed, and if necessary updated, including the components set out in part B of the Annex, by 22 December 2021 and every six years thereafter.

4. The likely impact of climate change on the occurrence of floods shall be taken into account in the reviews referred to in paragraphs 1 and 3.

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Chapter

6

Forest Fire Land Restoration

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Chapter 6

Forest Fire Land Restoration

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1 Postfire Effects on Ecosystems

1.1 Introduction

All disturbances produce impacts on ecosystems. The level and direction of impact (negative or positive) depends on ecosystem resistance and resilience, as well as on the severity of the disturbance. The variability in resource damage and response from site to site and ecosystem to ecosystem is highly dependent on burn or fire severity.

Fire severity (Burn severity) is a qualitative measure of the effects of fire onsite resources. As a physical- chemical process, fire produces a spectrum of effects that depend on interactions of energy release (intensity), duration, fuel loading and combustion, vegetation type, climate, topography, soil, and area burned.

Fire intensity is an integral part of burn severity, and the terms are often incorrectly used synonymously. Intensity refers to the rate at which a fire is producing thermal energy in the fuel-climate environment (DeBano and others 1998). Intensity is measured in terms of temperature and heat yield. Surface temperatures can range from 120 to greater than 2,730 °F (50 to greater than 1,500 °C). Heat yields per unit area can be as little as 59 BTU ft^{-2} (260 kg-cal m^{-2}) in short, dead grass to as high as 3700 BTU ft^{-2} (10,000 kg-cal m^{-2}) in heavy logging slash. Rate of spread is an index of fire duration and can vary from 1.6 ft $week^{-1}$ (0.5 m $week^{-1}$) in smouldering peat fires to as much as 15 mi hr^{-1} (25 km hr^{-1}) in catastrophic wildfires.

The component of fire severity that results in the most damage to soils and watersheds, and hence ecosystem stability, is duration. Fast moving fires in fine fuels, such as grass, may be intense in terms of energy release per unit area, but do not transfer the same amounts of heat to the forest floor, mineral soil, or soil organisms as do slow moving fires in moderate to heavy fuels. The impacts of slow moving, low or high intensity fires on soils are much more severe and complex. The temperature gradients that develop can be described with a linked-heat transfer model and are a function of moisture and fuel loadings.

Some aspects of fire severity can be quantified, but fire severity cannot be expressed as a single quantitative measure that relates to resource impact. Therefore, relative magnitudes of burn or fire severity, expressed in terms of the postfire appearance of litter and soil, are better criteria for placing burn or fire severity into broadly defined, discrete classes, ranging from low to high.

1.2 Fire Severity

Fire severity depends on the interaction between fire intensity (rate at which thermal energy is produced) and duration (length of time burning occurs at a particular point) and describes the magnitude of the disturbance and reflects the degree of change in ecosystem processes. Fire severity is a qualitative measure of the effects of fire on site and soil resources; it can occur along a spectrum from high to low or can be described as a patchwork, mosaic, matrix or mixed-severity event. Some researchers describe a light severity burn as one that burns only surface fuels, leaves the soil covered with partially charred organic material, and little to no duff consumption (fermentation (O_e) + humus (O_a) layers). A moderate-severity burn results from a large proportion of the organic material burned away from the surface of the soil and the remaining fuel is deeply charred. A high-severity burn results from all of the organic material burned away from the soil surface, organic material below the surface is consumed or charred. Fire severity has been assessed by numerous methods such as degree of destruction of aboveground live and dead biomass (Neary and others 2005), amount of forest floor consumed, particularly the duff layer, or heat penetration into the mineral soil.

Fire severity is defined in terms of: 1) the length of time fuel accumulates between fires and the amount of the accumulated fuels; 2) properties of the fuels (such as size, flammability, and moisture or mineral content); 3) how the fuels impact fire location and behaviour (causing crown, surface, or ground fires); and 4) heat transfer in the soil during the combustion of above-ground fuels and surface organic layers. High intensity fires - those that reach 1,200 degrees Celsius or more - do not always result in high severity impacts in the soil if their duration is short, but low intensity fires of just 300 degrees Celsius that smoulder for a long time in roots or organic matter can produce large changes in the nearby soil.

A general fire severity classification developed by Hungerford (1996) relates burn severity to the soil resource response (table 1).

Table 1. Fire severity classification based on postfire appearances of litter and soil and soil temperature profiles (Hungerford 1996, DeBano et al. 1998).

Soil and Litter Parameter	Burn Severity		
	Low	Moderate	**High**
Litter	Scorched, Charred, Consumed	Consumed	Consumed
Duff	Intact, Surface Char	Deep Char, Consumed	Consumed
Woody Debris - Small	Partly Consumed, Charred	Consumed	Consumed
Woody Debris - Logs	Charred	Charred	Consumed, Deeply Charred
Ash Color	Black	Light Colored	Reddish, Orange
Mineral Soil	Not Changed	Not Changed	Altered Structure, Porosity, etc
Soil Temp. at 0.4 in (10 mm)	<120 °F(<50 °C)	210-390 °F (100-200 °C)	>480 °F (>250 °C)
Soil Organism Lethal Temp.	To 0.4 in (10 mm)	To 2 in (50 mm)	To 6 in (160 mm)

1.3 Fire Regimes

"Fire regime" refers to the nature of fire occurring over long periods and the prominent immediate effects of fire that generally characterize an ecosystem. Descriptions of fire regimes are general and broad because of the enormous variability of fire over time and space. Classification of fire regimes into distinct categories faces the same difficulties and a dilemma that underlie any ecological classification. One difficulty is that putting boundaries around segments of biological processes that vary continuously involves some degree of arbitrariness. The dilemma is that for a classification to be useful to managers it must be practical and easily communicated, thus free of complexity. Yet to accurately reflect the nature of a biological process, such as response to fire, it must account for a complexity of interacting variables. A trade-off between practicality and accuracy or between simplicity and complexity is required. The fire regime concept brings a degree of order to a complicated body of fire behaviour and fire ecology knowledge. It provides a simplifying means of communicating about the role of fire among technical as well as nontechnical audiences.

Classifications of fire regimes can be based on the characteristics of the fire itself or on the effects produced by the fire. Fire regimes have been described by factors such as fire frequency, fire periodicity, fire intensity, size of fire, pattern on the landscape, season of burn, and depth of burn. The detail of a classification determines its best use. The more detailed classifications are primarily useful to ecologists and fire specialists attempting to describe and understand the more intricate aspects of fire. The simpler classifications are more useful for broadscale assessments and for explaining the role of fire to nontechnical audiences.

Heinselman (1978) and Kilgore (1981) produced the first classifications of fire regimes directed at forests. Two factors, fire frequency and intensity, formed the basis for their commonly referenced fire regime classifications. A difficulty with fire intensity is that a wide range of intensities, including crown fire and surface fire, can cause stand-replacement because mortality to aboveground vegetation is complete or nearly complete. Fire intensity relates only generally to fire severity. Severity of fire reflects (1) the immediate or primary effects of fire that result from intensity of the propagating fire front and (2) heat released during total fuel consumption. Plant mortality and removal of organic matter are the primary fire effects. Kilgore emphasized fire severity in his modification of Heinselman's fire regimes by referring to mortality of the primary tree cover as stand-replacement.

The fire regime classification (Figure 1) employed is based on fire severity. Characteristic fire frequencies are reported but not combined with fire severity into classes. Use of fire severity as the key component for describing fire regimes is appealing because it relates directly to the effects of disturbance, especially on survival and structure of the dominant vegetation. It is intended for broadscale applications and for communication about fire's role among resource managers and others interested in natural resources.

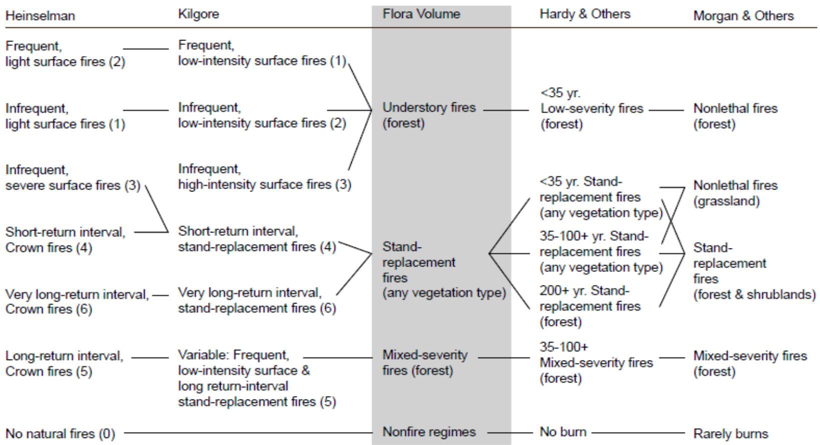


Figure 1-1—Comparison of fire regime classifications by Heinselman (1978), Kilgore (1981), Hardy and others (1998), Morgan and others (1998), and the Flora and Fuel Volume. Lines connect similar fire regime types. In parentheses, forest includes woodlands and grassland includes shrublands.

Figure 1. Comparison of fire regime classifications by Heinselman (1978), Kilgore (1981), Hardy and others (1998), Morgan and others (1998), and the Flora and Fuel Volume (Brown y Smith, 2000). Lines connect similar fire regime types. In parentheses, forest includes woodlands and grassland includes shrublands (From Brown and Smith, 2000)

The following describes the fire regime types:

1. Understory fire regime (applies to forests and woodlands). Fires are generally nonlethal to the dominant vegetation and do not substantially change the structure of the dominant vegetation. Approximately 80 percent or more of the aboveground dominant vegetation survives fires.

2. Stand-replacement fire regime (applies to forests, woodlands, shrublands, and grasslands). Fires kill aboveground parts of the dominant vegetation, changing the aboveground structure substantially. Approximately 80 percent or more of the aboveground dominant vegetation is either consumed or dies as a result of fires.

3. Mixed severity fire regime (applies to forests and woodlands)—Severity of fire either causes selective mortality in dominant vegetation, depending on diffe-

rent tree species' susceptibility to fire, or varies between understory and stand-replacement.

4. Nonfire regime—Little or no occurrence of natural fire.

Most belowground plant parts survive, allowing species that sprout to recover rapidly. This is true of tundra, grasslands, and many shrub- land ecosystems. Some authors consider grasslands to have "nonlethal" fire regimes based on the criterion that structure and composition of vegetation is similar to the pre-burn condition within 3 years after a burn. Because fire radically alters the structure of the dominant vegetation for at least a short time, however, we consider grassland ecosystems to have stand-replacement fire regimes. Because grassland, tundra, and many shrublands are stand-replacement fire regime types, a more interesting aspect of fire regimes in these ecosystems is fire frequency, which can vary substantially and have a major influence on vegetation composition and structure.

The understory and mixed severity fire regimes apply only to forest and woodland vegetation types. The mixed severity fire regime can arise in three ways:

- Many trees are killed by mostly surface fire but many survive, usually of fire resistant species and relatively large size.
- Severity within individual fires varies between understory burning and stand-replacement, which creates a fine-grained pattern of young and older trees. This kind of fire regime has not been recognized in previous classifications. It probably occurs because of fluctuations in weather during fires, diurnal changes in burning conditions, and variation in topography, fuels, and stand structure within burns. Highly dissected terrain is conducive to this fire regime. In actuality, a blend of these two mixed severity types probably occurs.
- Fire severity varies over time with individual fires alternating between understory burns and stand-replacement.

1.4 Fire Effects on Watersheds

Soils, vegetation, and litter are critical to the functioning of hydrologic processes. Watersheds with good hydrologic conditions and adequate rainfall sustain stream baseflow conditions for much or all of the year and produce little sediment. With good hydrologic condition (greater than 75 percent of the ground covered with vegetation and litter), only about 2 percent or less of rainfall becomes surface runoff, and erosion is low. When site disturbances, such as severe fire, produce hydrologic conditions that are poor (less than 10 percent of the ground surface covered with plants and litter), surface runoff can increase over 70 percent and erosion can increase by three orders of magnitude.

Within a watershed, sediment and water responses to wildfire are often a function of fire severity and the occurrence of hydrologic events. For a wide range of fire severities, the impacts on hydrology and sediment loss can be minimal in the absence of precipitation. However, when a precipitation event follows a large, moderate- to high-burn severity fire, impacts can be far reaching. Increased runoff, peak flows, and sediment delivery to streams can affect fish populations and their habitat.

Fire can destroy accumulated forest floor material and vegetation, altering infiltration by exposing soils to raindrop impact or creating water repellent conditions. Loss of soil from hillslopes produces several significant ecosystem impacts. Soil movement into streams, lakes, and riparian zones may degrade water quality and change the geomorphic and hydrologic characteristics of these systems. Soil loss from hillslopes may reduce site productivity.

In general, the magnitude of measured increases in water yield the first year after fire can vary greatly within a location or between locations depending on fire severity, climate, precipitation, geology, soils, topography, vegetation type, and proportion of the vegetation burned. Because increases in water yield are primarily due to elimination of plant cover, with subsequent reductions in the transpiration component of ET, flow increases are greater in humid ecosystems with high pre-fire ET. Elevated stream flow declines through time as woody and herbaceous vegetation regrow, with this recovery period ranging from a few years to decades.

The effects of fire disturbance on storm peak flows are highly variable and complex. They can produce some of the most profound watershed and riparian impacts that forest managers have to consider. Intense short duration storms that are characterized by high rainfall intensity and low volume have been associated with high stream peak flows and significant erosion events after fires.

Burned watersheds generally respond to rainfall faster than unburned watersheds, producing more "flash floods". Water repellent soils and cover loss will cause flood peaks to arrive faster, rise to higher levels, and entrain significantly greater amounts of bedload and suspended sediments. Flood warning times are reduced by "flashy" flow, and the high flood levels can be devastating to property and human life. Although these concepts of storm flow timing are well-understood within the context of wildland hydrology, some studies have confounded results because of the combined changes in volume, peak and timing at different locations in the watershed, and the severity and size of the disturbance in relation to the size of watershed.

1.4.1 Surface Runoff and Erosion

Sediment yields after one year of prescribed burns and wildfires range from very low, in flat terrain and in the absence of major rainfall events, to extreme, in steep terrain affected by high intensity thunderstorms. Erosion on burned areas typically declines in subsequent years as the site stabilizes, but the rate varies depending on burn or fire severity and vegetation recovery. Soil erosion after fires can vary from under 0.4 to 2.6 t ac^{-1} yr^{-1} (0.1 to 6 Mg ha^{-1} yr^{-1}) in prescribed burns and from 0.2 to over 49 t ac^{-1} yr^{-1} (0.01 to over 110 Mg ha^{-1} yr^{-1}) in wildfires (Robichaud and Brown 1999).

Water repellency

Wildland fires are often landscape-scale disturbances that can alter the hydrologic and erosion responses of catchments. Erosion can occur when ground cover is reduced or consumed, and subsequently infiltration rates are reduced, i.e., water repellency is high. Fire-induced or enhanced soil water repellency (hydrophobicity) is commonly viewed as a key contributor to the substantial increases in hillslope runoff and erosion observed following severe wildfire.

Soils do not all exhibit the same degree of water repellency; a water-repellent soil is classified as one on which a drop of water will not spontaneously penetrate. Water drop penetration time (WDPT) has been used extensively to characterize soil water repellency. Several factors associated with fire, such as removal of surface litter and higher raindrop impact, would produce higher runoff and erosion from burned compared with unburned catchments, independent of water repellency. High runoff and erosion occurs from the combined effects of canopy destruction and water repellency induced by fire, typically higher water repellency results from high severity fires.

1.4.2 Sediment Yield and Channel Stability

Severe wildfires can cause damage to plant cover and, thus, increase stream flow velocity, sediment delivery to streams, and stream water temperatures, as contrasted to low severity, cool-burning prescribed fires, which have less severe consequences. If surface erosion via overland flow reaches stream channels, then stream sediment concentrations increase proportional to the sediment delivered. Excess sediment is the principal pollutant of stream water associated with forest management and is considered the primary threat to the integrity of aquatic resources. After fire, excess sediment delivery to streams typically occurs after a measurable storm event. Watersheds severely denuded by fire are vulnerable to accelerated rates of soil erosion. While many fires increase sediment transport, wildfire often produces more sediment than prescribed fire. Generally, prescribed fires, by their design, are not intended to consume extensive layers of forest floor litter. Without sediment transport via overland flow or surface runoff, input of sediment to streams would be minimal following prescribed fire or wildfire. If the forest floor remains intact and little to no bare soil is exposed, there is no mechanism for long-distance transport of sediment to streams, regardless of rainfall event.

In some regions, over 60 percent of the total landscape sediment production over the long-term is fire-related. Much of that sediment loss can occur the first year after a wildfire. Consequently, postfire treatments that have an impact the first year can be important in minimizing damage to both soil and watershed resources.

After fires, suspended sediment concentrations in stream flow can increase due to the addition of ash and silt-to-clay sized soil particles in stream flow. High turbidity reduces municipal water quality and can adversely affect fish and other aquatic organisms. It is often the most easily visible water quality effect of fires. Less is known about turbidity than sedimentation in general because it is difficult to measure, highly transient, and extremely variable.

A stable stream channel reflects a dynamic equilibrium between incoming and outgoing sediment and stream flow. Increased erosion after fires can alter this equilibrium by transporting additional sediment into channels (aggradation). However, increased peak flows that result from fires can also produce channel erosion (degradation). Sediment transported from burned areas as a result of increased peak flows can adversely affect aquatic habitat, recreation areas, roads, buildings, bridges, and culverts. Deposition of sediments alters habitat and can fill in lakes and reservoirs.

1.4.3 Mass Wasting

Mass wasting includes slope creep, rotational slumps, debris flows and debris avalanches. Slope creep is usually not a major postfire source of sediment. Rotational slumps normally do not move any significant distance. Slumps are only major problems when they occur close to stream channels, but they do expose extensive areas of bare soil on slope surfaces. Debris flows and avalanches are the largest, most dramatic, and main form of mass wasting that delivers sediment to streams. They can range from slow moving earth flows to rapid avalanches of soil, rock, and woody debris. Debris avalanches occur when the mass of soil material and soil water exceed the sheer strength needed to maintain the mass in place. Steep slopes, logging, road construction, heavy rainfall, and fires aggravate debris avalanching potential.

Many fire-associated mass failures are correlated with development of water repellency in soils. Chaparral vegetation in the South-western United States is a high hazard zone because of the tendency to develop water repellent soils. Water repellency also occurs commonly elsewhere in the West after wildfires. Sediment delivery to channels by mass failure can be as much as 50 percent of the total postfire sediment yield. For example, wildfire in chaparral vegetation in coastal southern California increased debris avalanche sediment delivery from 18 to 4,845 yd mi^{-2} yr^{-1} (7 to 1,910 m^3 km^{-2} yr^{-1}).

Some authors describe two types of debris flow initiation mechanisms, infiltration soil slip and surface runoff after wildfires. Of these, surface runoff which increases sediment entrainment is the dominate triggering mechanism.

1.4.4 Dry Ravel

Dry ravel is the gravity-induced downslope surface movement of soil grains, aggregates, and rock material, and is a ubiquitous process in semiarid steepland ecosystems. Triggered by animal activity, earthquakes, wind, and perhaps thermal grain expansion, dry ravel may best be described as a type of dry grain flow. Fires greatly alter the physical characteristics of hillside slopes, stripping them of their protective cover of vegetation and organic litter and removing barriers that were trapping sediment. Consequently, during and immediately following fires, large quantities of surface material are liberated and move downslope as dry ravel. Dry ravel can equal or exceed rainfall-induced hillslope erosion after fire in chaparral ecosystems.

1.4.5 Water Quality

Increases in stream flow after fire can result in substantial to little effect on the physical and chemical quality of streams and lakes, depending on the size and severity of the fire. Higher stream flows and velocities result in additional transport of solid and dissolved materials that can adversely affect water quality for human use and damage aquatic habitat. The most obvious effects are produced by suspended and bedload sediments, but substantial changes in anion/cation chemistry can occur.

Undisturbed forest, shrub, and range ecosystems usually have tight cycles for major cations and anions, resulting in low concentrations in streams. Disturbances such as cutting, fires, and insect outbreaks interrupt or temporarily terminate uptake by vegetation and may affect mineralization, microbial activity, nitrification, and decomposition. These processes result in the increased concentration of inorganic ions in soil which can be leached to streams via subsurface flow. Nutrients carried to streams can increase growth of aquatic plants, reduce the potability of water supplies, and produce toxic effects.

Most attention relative to water quality after fire focuses on nitrate nitrogen (NO_3-N) because it is highly mobile. High NO_3-N levels, in conjunction with phosphorus, can cause eutrophication of lakes and streams. Most studies of forest disturbances show increases in NO_3-N, with herbicides causing the largest increases.

1.4.6 Precipitation Regime

After fire, rainfall intensity and duration can influence the amount of sediment delivered to a stream channel. The detachment of soil particles by rainsplash or overland flow and their transfer downslope are sensitive to modifications in land surface properties caused by fire. In low rainfall ecosystems, surface runoff and erosion may not be observed if there is a long period of post-fire recovery before the first rainfall event. Even in ecosystems with low mean annual rainfall, a high-intensity rainstorm immediately after wildland fire can create runoff that alters the topography of the hillslope, which subsequently impacts stream channels. Rainstorm events need to have enough energy to transport sediment. Some researchers determined that rainfall events of >50 mm hr^{-1} were required to transport material after a fell-and-burn prescribed fire in the southern Appalachians. Sediment yields are typically higher in the first year after burning, especially when the burned watershed has been exposed to high-intensity rainfall events immediately after the fire has exposed the soil surface. Some of the largest increases in surface runoff have been observed where short- duration, high intensity convective rainstorms occur. For example, after the 1996 Buffalo Creek Fire in Colorado (USA), two short-duration, high-intensity rainstorms (90 mm hr^{-1}) removed ash from the hillslopes, rilled the hillslope surfaces, channelized subtle drainages, which led to a headward extension of the channel network, and deposited sediment in stream channels.

1.4.7 Vegetation Recovery

Post-fire soil erosion amounts vary not only with rainfall but also with burn severity, topography, soil characteristics and amount of vegetative recovery. Under moderate to severe fire severity that removes vegetation and forest floor cover, transpiration, interception and surface storage capacity for rain are temporarily reduced. Conversely, any fire- induced alterations to storage capacity and water repellency will decline as vegetation and ground litter recover. Ground cover protects the soil from raindrop impact and offers resistance to overland flow. Vegetation recovery rates are strongly affected by fire size and severity, post-fire erosion events and vary by climate and geographic area. Rapid vegetation establishment has been regarded as the most cost-effective method to promote water infiltration and reduce hillslope erosion.

Postfire hillslope rehabilitation treatments include seeding for vegetative re-growth, ground covers or mulches, and barrier and trenches that physically hold runoff and sediment. For example, in the eastern of United States, such costly and dramatic post-fire rehabilitation efforts are typically not required. Even after severe fire, recovery rates of southern Appalachian watersheds are much faster than western forests due to rapid vegetative re-growth.

Low severity burning, such as prescribed fires, can promote a herbaceous flora increase plant available nutrients, and thin-from-below over-crowded forests. While large, severe fires can cause changes in successional rates, alter species composition, generate volatilization of nutrients and ash entrainment in smoke columns, produce rapid or decreased soil mineralization rates, and result in subsequent nutrient losses through accelerated erosion.

1.4.8 Stream Nitrogen

The potential for increased No_3-N in stream flow after burning is attributed mainly to accelerated mineralization and nitrification and reduced plant uptake. Several studies on effects of prescribed fire on stream water quality, have found little to no detectable changes in stream water chemistry after burning. For the few cases where a measurable increase in No_3-N was detected, timing of wildland fire influenced No_3-N delivery to streams. In the spring, less No_3-N will be transported to streams when vegetation uptake and microbial immobilization are typically high, compared to burns in the fall when vegetation is dormant.

For example, some studies compared stream No_3-N responses from watersheds burned in the fall and those burned in the spring. Two sites burned in the fall showed a stream No_3-N response, whereas the sites that were burned in the spring showed no response.

1.5 Important Notes

When a wildland fire occurs, the principal concerns for changes in water quality are delivery of sediment and nutrients, particularly nitrate, into the stream channel. Fire managers can influence the effects of prescribed fire on water quality by limiting fire severity, limiting fire size, and avoiding burning on steep slopes. Wildfires are typically larger and more severe consuming more fuel and releasing more nutrients than prescribed fire, which increases susceptibility to erosion of soil and nutrients into the stream. A wide array of studies, support the following conclusions:

1. Maintaining an intact forest floor and promoting rapid vegetation recovery is critical to minimizing the magnitude and duration of sediment transport (surface erosion), sediment delivery (suspended solids) and subsequent water quality responses,

2. Burned areas are most vulnerable to surface erosion immediately post-fire and during extreme rainfall events,

3. Generally, water quality responses are much lower in a moderate topography, lower fire severity, and rapid vegetation recovery

The regional differences on postfire effects, emphasize the need for localized assessment and analyses of fire prescriptions, post-wildfire rehabilitation, and associated monitoring efforts.

2 Postfire Assessment Fire Effects Information System

2.1 Introduction

The Fire Effects Information System (FEIS) is an easy to use, computerized knowledge management system, created by the Forest Service of United States Department of Agriculture, that stores and retrieves current information as organized in an encyclopedic fashion and it can be adapted to any region in the world. FEIS provides: effects and related biological, ecological, and management information in three major categories: plant species, wildlife species, and plant communities. The community category includes three levels of classification: an ecosystem level, a Kuchler potential natural vegetation type level (Kuchler, 1964), and a cover type level. For each category and level, the system provides information for various predetermined topics for several subject matter areas.

At present, the knowledge management tools are not powerful enough to save researchers and practitioners precious time and money. The knowledge base is too often largely ignored because it is too costly to find and process the needed information. In other words, much of the scientific and technical knowledge is not useful.

FEIS was created to deal with exactly this knowledge management problem. The solution involves structuring knowledge: assimilating and thereby compacting research results into an organized framework. While not explicitly designed and developed to conform with a preconceived knowledge management model.

A consequence of poor knowledge management is the perception that knowledge on a particular subject does not exist. Such a perception prevails among many wildland fire managers and resource specialists regarding information on the effects of fire on plants, animals, and plant communities. Increased use or desire to use prescribed fire in land and resource management has created an unprecedented demand for species-specific fire effects information. Because such information is in a large and diverse literature, it is difficult to identify and obtain, especially by field-based managers.

Even if obtained, synthesis is often difficult because results frequently are not readily or easily comparable due to differences in type of fire, season of year, fuel moistures, and other variables that may be poorly defined or perhaps not measured at all. FEIS provides ready and easy access to the state of knowledge on fire effects on plants, wildlife, and plant communities, and supports application of prescribed fire in particular and fire management in general.

2.2 The Knowledge Base

The FEIS knowledge base contains information in three major categories: plant species, wildlife species, and plant communities. The plant communities' category includes three levels of classification: a broad ecosystem level, a potential natural vegetation type level, and a cover type level. For each category and level, the knowledge base contains a summary of state-of-the- knowledge information for various topics within each of several subject matter areas (Figure 2).

2.3 Plant Species Information

In the FEIS knowledge base, information regarding any plant species is accessed using the scientific name of the desired plant or a corresponding abbreviation of the scientific name. The abbreviation is derived from the first three letters of the genus and the first three letters of the species. For plant infrataxa, the first letter of the subspecies or the variety is added to the end of the basic six-letter abbreviation. If the above method assigns identical abbreviations for two or more species, the abbreviation is assigned to the species with the widest distribution.

The other species are abbreviated using the first three letters of the genus and the first, second, and fourth letter of the species scientific name. For example:

Lycium andersonii is abbreviated as LYCAND

Pinas contorta var. latifolia is abbreviated as PINCONL

Pinus monophylla is abbreviated as PINMON

Pinus monticola is abbreviated as PINMOT

Plant species summaries in the FEIS knowledge base are organized under the eight subjects shown in Figure 2. A topic-by-topic description of information available in each subject is presented in Table 2.

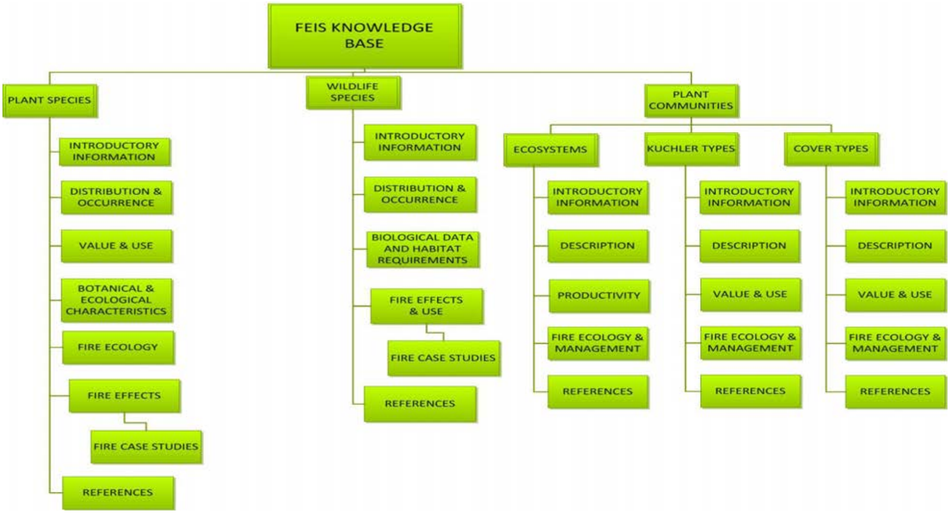


Figure 2. Subject matter content of the FEIS knowledge base

Table 2. Plant species information contained in the Fire Effects Information System knowledge base.

Information topic by subject matter area	Information provided In species summary
	1. Introductory species Information
Species	Scientific name of the plant species.
Abbreviation	Six- or seven-letter abbreviation for the plant. Used as keyword in CRS.
Synonyms	Fully documented scientific names of synonyms that are in current use or occur frequently in the literature.
SCS plant code	Plant code used by the Natural Resources Conservation Service (U.S. Department of Agriculture, Soil Conservation Service 1994).
Common names	Common names of the plant. The name most often used in the literature appears first on the list and is used throughout the summary. Other frequently used common names are also listed.

Taxonomy	The fully documented scientific name for the plant; a list of the currently recognized subspecies, varieties, and forms; and a brief discussion of other taxonomic information.
Life form	Life form of the plant, from the following list:
	Tree
	Shrub
	Vine
	Graminoid
	Forb
	Cactus
	Fern or Fern Ally
Federal legal status	Current Federal legal status of the plant
Other status	Brief statement of threatened, rare, or other status for States, regions, National Parks, and National Forests. Also includes Federal legal status of varieties or subspecies.
Compiled by and date	Full name of compiler and date entered.
Last revised by and date	Full name of revisor and date revised.
Authorship and citation	Correct citation for the species summary.
2. Distribution and occurrence	
General distribution	Brief description of the plant's distribution in broad geographic terms.
Ecosystems	Forest and Range Environmental Study (FRES) ecosystems in which the plant occurs. Some FRES ecosystems are described in the FEIS knowledge base
States	Country Provinces in which the plant occurs, listed by two-letter postal code abbreviation
Administrative units	National Park Service units in which the plant occurs.
BLM physiographic regions	Bureau of Land Management physiographic regions in which the plant occurs.

Kuchler plant associations	Kuchler Plant Associations (Kuchler 1964) in which the plant occurs.
SRM cover types	Foresters cover types in which the plant occurs (Eyre 1980).
Habitat types and plant communities	Plant's role in habitat type and community type classifications, a list of classifications in which the plant is used as an indicator or dominant, and a list of some associated plant species.
3. Value and use	
Wood products value	Important wood products derived from species.
Importance to livestock and wildlife	Plant's importance as food and cover for livestock and wildlife.
Palatability	Plant's palatability to livestock and wildlife, including palatability ratings and seasonal variation.
Nutritional value	Nutritive characteristics of the plant, such as energy content and protein content.
Cover value	Degree to which the plant provides environmental protection for wildlife.
Value for rehabilitation of disturbed sites	Use of the plant to revegetate disturbed areas. Information on seeding, site preparation, and other factors associated with use of the plant for rehabilitation.
Other uses and values	Uses and values of the plant other than those indicated above, such as historical, medicinal, or food use.
Management considerations	Important factors in the management of the plant for timber, range, wildlife, or other purposes.
4. Botanical and ecological characteristics	
General botanical characteristics	Description of the plant, especially characteristics that pertain to management and fire, such as season of occurrence, size, longevity, and type of stem, leaves, and roots. Not a complete description of the plant for use in identification.
Raunkiaer life form	Life form based on Raunkiaer's (1934) system of classifying plants by the placement of their perennating meristem in relation to the soil surface.
Regeneration processes	How the plant regenerates (sexually and vegetatively) and the biological and environmental conditions necessary for successful regeneration. Describes seed major barriers to successful regeneration production and viability.

Site characteristics	General site characteristics, including soils, elevation, topography, climate, and moisture regimes. Describes geographic variation in site conditions.
Successional status	Successional classification of species, shade tolerance, and other factors indicating the plant's role in community dynamics.
Seasonal development	Seasonal trends in plant development and important factors that control development; geographic variation in development.
5. Fire ecology	
Fire ecology or adaptations	Plant's susceptibility to fire and its ability to resist damage by fire. Attributes of the plant that account for its ability to survive fire. Information on fire regimes, fuels, and fire characteristics.
Postfire regeneration strategy	Method(s) by which the plant survives or recolonizes burned areas.
6. Fire effects	
Immediate fire effects	Immediate effects of fire on plant; variation in effects due to fire severity, season, and other plant variables.
Discussion and qualification of fire effects	Details regarding immediate fire effects; description of specific situations and circumstances that result in fire effects differing from those described above.
Plant response to fire	Response of the plant species following fire, including immediate postfire response (first growing season following fire) and long-term response (subsequent growing seasons).
Discussion and qualification of plant response	Details regarding plant response; description of specific situations and circumstances that result in plant responses differing from those described above.
Fire management considerations	Implications of fire effects and plant response information for fire management. May include discussion of prescribed fire planning, fire exclusion, and fuel management.
7. Fire case studies	
Case name	Concise, general description of the fire case study and location.
References	Author(s) and date of papers describing the case study; these papers are also included in the REFERENCES section.
Season/severity classification	Season of burning/fire severity (such as "fall/severe").
Study location	Exact location of study sites, if known.

Pre fire vegetative community	Prefire plant community and habitat types; community age, structure, disturbance history.
Target species phonological state	Phonological state of plant species at time of burning.
Site description	Site characteristics, including soils, elevation, topography, and climate; preburn fuel loadings; study design, including size of study plots and description of preburn treatments.
Fire description	Burning conditions, including weather and fuel moistures; firing methods and type of burn; fire behaviour and fire severity.
Fire effects on target species	Survival, mortality, and damage to plant species after burn; regeneration, establishment success.
Fire management implications	Summary of study's conclusions and recommendations regarding plant species.

2.4 Wildlife Species Information

Knowledge base information regarding any wildlife species is accessed using the scientific name of the species or a corresponding four-letter abbreviation of the scientific name. The abbreviation is derived from the first two letters of the genus plus the first two letters of the species name. For example, Bonasa umbellus, ruffed grouse, is abbreviated as BOUM.

Wildlife species summaries in the FEIS knowledge base are organized under the six subjects shown in Figure 2. A topic-by-topic description of information available in each subject is presented in Table 3.

Table 3. Wildlife species information contained in the Fire Effects Information System knowledge base.

Information topic by subject matter area	Information provided In species summary
1. Introductory species Information	
Wildlife species	Scientific name of the animal species.
Abbreviation	Four-letter abbreviation for the animal.

Common names	Common names of the animal.
Taxonomy	The fully documented scientific name for the animal; a list of the currently recognized subspecies; and a brief discussion of other taxonomic information.
Order	Order to which the animal belongs.
Class	Class to which the animal belongs.
Federal legal status	Current Federal legal status of the animal.
Other status	Brief statement of threatened, rare, or other status for States, regions, National Parks, and National Forests. Also includes Federal legal status of subspecies.
Compiled by and date	Full name of compiler and date entered.
Last revised by and date	Full name of revisor and date revised.
Authorship and citation	Correct citation for the species summary.
2. Wildlife distribution and occurrence	
General distribution	Brief description of the animal's distribution in broad geographic terms.
Ecosystems	Forest and Range Environmental Study (FRES) ecosystems in which the animal occurs.
States	Country Provinces in which the animal occurs, listed by two-letter postal code abbreviation
Administrative units	National Park Service units in which the animal occurs, listed by National Park Alpha Organizational Code.
physiographic regions	Physiographic regions in which the animal occurs.
Küchler plant associations	Kuchler plant associations in which the animal occurs.
cover types	Foresters cover types in which the animal occurs.
RM cover types	Range Management cover types in which the animal occurs.
Plant communities	Brief description of the different vegetative communities that make up the animal's habitat.
3. Biological data and habitat requirements	
Timing of major life history events	Information on life span, age at maturity, and months or seasons when reproductive events occur.

Preferred habitat	Usual or optimum habitat at different times of year or during different times in life cycle.
Cover requirements	Cover required for reproduction or other needs.
Food habits	Types of food usually used and preferences related to age and reproductive status; list of important food species.
Predators	Animals that prey on the species, including humans.
Management considerations	Important factors in habitat management to benefit the animal; effects of the animal on its habitat; diseases or other threats to the animal.
4. Fire effects and use	
Direct fire effects on animals	Direct effects of fire on individuals; variation due to fire severity, season, frequency, and other variables.
Habitat related fire effects	Effects of fire or fire exclusion on the animal's habitat; variation in effects due to fire frequency, severity, season, and other variables.
Fire use	Ways in which fire has been used or can be used to affect the animal or its habitat.
5. Fire case studies	
Case name	Concise description of case study and location.
References	Author(s) and date of papers describing the case study
Season/severity classification	Season of burning/fire severity.
Study location	Exact location of study sites, if known.
Prefire habitat	Pre-fire plant community and habitat types; community age. Structure, disturbance history.
Site description	Site characteristics, including soils, elevation, topography, and climate; pre-burn fuel loadings; study design, including size of study plots and description of pre-burn treatments.
Fire description	Burning conditions, including weather and fuel moistures; firing methods and type of burn; fire behaviour and fire severity.
Fire effects on animal species	Survival, mortality, and damage to animal species after burn; regeneration, establishment success.
Fire management implications	Summary of study's conclusions and recommendations regarding animal species.

2.5 Plant Community Information

This information in the FEIS knowledge base is organized under five subjects for each of three levels of classification as shown in Figure 1. The broadest level of plant community classification represented in FEIS is the forest and range environmental study (FRES) ecosystem classification (Garrison and others 1977). The next level is the Kuchler potential natural vegetation type (Kuchler 1964). The final level of plant community classification in FEIS is the cover type. A topic-by-topic description of information available in each FRES ecosystem subject is presented in Table 4. Similar descriptions for Kuchler potential natural vegetation types and for cover types are presented in Tables 5 and 6.

Table 4. Ecosystem information contained in the Fire Effects Information System knowledge base

Information topic by subject matter area	Information provided In plant community summary
1. Ecosystem Information	
Ecosystem	Name of the Forest and Range Environmental Study (FRES) ecosystem.
Forest and range environmental study number	Number of the FRES ecosystem
Definition	Definition of the FRES ecosystem.
Compiled by and date	Full name of compiler and date entered.
Last revised by and date	Full name of revisor and date revised.
Authorship and citation	Correct citation for the plant community summary.
2. Ecosystem description	
Physiography	Geographic areas where the FRES ecosystem occurs and characteristic topography.
Climate	Brief description of climate, including average precipitation and temperature patterns.
Soils	Brief description of soils and parent materials.
Vegetation	Dominant species and important associated species.
Wildlife	Animal species commonly found in the ecosystem.
Land use	Brief description of current land use patterns in the ecosystem.

3. Ecosystem productivity	
Productivity	Herbage and browse productivity description
Characteristics of productivity classes	Description of specific areas or vegetation communities within the ecosystem in terms of productivity.
Summary of production	Table describing productivity according to class.
Condition and trend	Current condition of the productivity classes and patterns of change.
4. Ecosystem fire ecology and management	
Fuels, flammability, and fire occurrence	Information on fuel quantities and distribution, historic and current fire regimes, and characteristic fire behaviour.
Fire effects	Direct and indirect effects of various fire regimes and fire exclusion on dominant plant communities in the ecosystem.
Fire management considerations	Implications of fire ecology information for fire management. May include general guidelines for use of prescribed fire and fuel management.

Table 5. Kuchler potential natural vegetation type information contained in the Fire Effects Information System knowledge base.

Information topic by subject matter area	Information provided In plant community summary
1. Kuchler type Information	
Kuchler type	Name of type from Kuchler (1964)
Kuchler type number	Type number from Kuchler (1964).
Physiognomy	Kuchler's (1964) description of structure of climax community.
Occurrence	States in which the type occurs.
Compiled by and date	Full name of compiler and date entered.
Last revised by and date	Full name of revisor and date revised.
Authorship and citation	Correct citation for the plant community summary.

2. Kuchler type description	
Physiography	Topographic and hydrological characteristics of sites where the type occurs.
Climate	Description of climate, including length of growing season, and precipitation and temperature patterns.
Soils	Parent material, texture, classification, and composition of soils in the type.
Vegetation	Dominant species in the type and important associated species. Includes list of publications that list dominant vegetation as community or habitat type.
Wildlife	Animal species commonly found in the type and those with Federal legal status.
Ecological relationships	Variation and change in plant communities within the type, particularly as they relate to autecology of important species, patterns of disturbance, hydrological conditions, and succession.
3. Kuchler type value and use	
Forestry values	Importance and productivity of timber species in the type.
Range values	Importance of grazing and productivity values.
Wildlife values	Use of the type by animal species.
Other values	Other uses of the type.
Management concerns	Important factors in preservation or management of the type; historic or current threats to the type.
4. Kuchler type fire ecology and management	
Fuels, flammability, and fire occurrence	Quantity and continuity of fuels in the type; historic and current fire regimes in the type, including frequency and severity of fires.
Fire effects on site	Effects of fire on soils, nutrient content, and hydrology; variation due to season, frequency, and severity of fires.
Fire effects on vegetation	Direct and indirect effects of fire on structure and composition of plant community; variation due to season, frequency, and severity of fires; patterns of postfire succession.
Fire effects on resource management	Effects of fire related to forestry, range, wildlife, and other management objectives.

Fire use considerations	Guidelines or concerns relating to use of prescribed fire, particularly fire behaviour and fuel management.
Fire management considerations	Implications of fire effects information for fire management, including both fire exclusion and prescribed fire.
Rehabilitation of sites following wildfire	Guidelines for accelerating or altering succession after fire.

Table 6. Cover type information contained in the Fire Effects information System knowledge base.

Information topic by subject matter area	**Information provided In plant community summary**
1. Cover type Information	
Cover type	Name of the cover type.
Definition	Criteria that describe the cover type; usually in terms of dominant species.
Occurrence	Geographic distribution and extent of cover type.
Compiled by and date	Full name of compiler and date entered.
Last revised by and date	Full name of revisor and date revised.
Authorship and citation	Correct citation for the plant community summary.
2. Cover type description	
Site characteristics	Topography, soils, and moisture regimes characteristic of the type.
Vegetation	Species composition and structure of plant communities in the type.
Common species	Lists of common species in the following classes: TREES. SHRUBS. GRAMINOIDS. FORBS, and OTHER.

Ecological relationships	Variation and change in plant communities within the type, particularly as they relate to autecology of important species, patterns of disturbance, and succession.
3. Cover type value and use	
Forestry values	Importance and productivity of timber species in the type.
Range values	Importance of grazing and productivity values.
Wildlife values	Use of the type by animal species.
Other values	Other important uses of the type.
Management concerns	Important factors in preservation or management of the type; historic or current threats to the type.
4. Cover type fire ecology and management	
Fuels, flammability, and fire occurrence	Quantity and continuity of fuels in the type; historic and current fire regimes in the type, including frequency and severity of fires.
Immediate fire effects on the site	Effects of fire on soils, nutrient content, and hydrology; variation due to frequency, season, and severity of fires.
Initial vegetative response to fire	Direct effects of fire on structure and composition of plant community; indirect effects of fire during first growing season after fire.
Long-term vegetative response to fire	Effects of fire on structure, composition, and succession during subsequent growing seasons.
Fire effects on forestry	Effects of fire on timber production, site quality, and other forestry values.
Fire effects on grazing	Effects of fire on forage productivity.
Fire effects on wildlife	Effects of fire on animals and their habitat.
Fire effects considerations	Guidelines or concerns about use of prescribed fire, particularly fire behaviour and fuel management.
Fire management considerations	Implications of fire effects information for fire management, including both fire exclusion and prescribed fire.
Rehabilitation of sites following wildfire	Guidelines for accelerating or altering succession after fire.

3 Erosion control. postfire restoration treatments

3.1 Introduction

Slope protection and erosion control entail the integrated or conjunctive use of plants and structures. Plants can be introduced and established in and around structural systems, under the category of "mixed construction" methods. Plants can be introduced, for example, on the benches of tiered retaining wall systems or, alternatively, they can be inserted and established in the interstices or frontal openings of porous revetments, cellular grids, and retaining structures. They can also be introduced in and around check dams.

3.2 Role and Function of Structural Components

Structural components of biotechnical earth support and slope protection systems must be capable of resisting external forces causing sliding, overturning, and bearing capacity failure. In addition these structures must resist internal forces that cause shear, compression, and bending stresses. In the case of revetments or slope armor systems, the armor units must have sufficient weight and interlocking to resist displacement under wave action or tractive stresses exerted flowing water.

3.3 Retaining Structures

Retaining structures are designed to resist fairly large, lateral earth forces without excessive displacement or rotation. Gravity structures resist these external forces primarily as a result of their weight. Crib, gabion, cantilever, and reinforced earth walls are examples of gravity structures. Structures with porous faces or frontal openings lend themselves to vegetative treatment. Vegetation can also be introduced on the benches of tiered or stepped-back retaining structures (Figure 3).

Figure 3. Construction of Retaining Structures (Source: Tardío, G.)

3.4 Revetments

Revetments are designed primarily to armor a slope against scour and erosion from wave action and streamflow. They are not designed to resist large lateral earth forces and normally are placed on slopes no steeper than 1.5:1 *(H:V).* Revetments resist displacement by the weight and interlocking characteristics of the armor units. A revetment must be placed on a suitable filter course or blanket to avoid washout of fines or soil behind the armor units (Figure 4).

Figure 4. Example of revetments (source: barnstondale.org.uk)

3.5 Articulated Block Walls

Articulated block walls and rock breast walls are not designed to resist large lateral earth forces. They provide some lateral earth support and protection to the toe of slopes. Articulated block walls resist external forces primarily by their weight. The resultant earth force acting on the wall is reduced considerably by battering or inclining the wall against a slope. Local shear displacement between the blocks (or rocks) is resisted by friction and interlocking (or articulation) between the structural units (Figure 5).

Figure 5. Examples of Articulated block walls and rock breast walls (Source: llnkgroup.com and amseek.com)

3.6 Slope Gratings (Three-Dimensional Cellular Grids)

A slope grating or cellular grid provides some restraint or lateral earth support; however, its main purpose is to facilitate and permit the establishment of vegetation on steep slopes, that is, slopes steeper than 1.5:1 *(H : V)*. A slope grating system covers bare slopes that are vulnerable to rapid weathering and slaking disintegration when exposed (Figure 6).

Figure 6. Examples of cellular grid (source: Tardio, G.)

3.7 Postfire Restoration Planning

3.7.1 Restoration Planning

In postfire ecosystems, some general principles underlying behind the restoration planning. First, the impacts of forest fires are inexorably linked with previous degradation processes by human-activities. Furthermore, postfire restoration in the medium to long term, should include an integrity recovery of the ecosystem in an ecological sense, in terms of composition, structure and functioning also including the self-regeneration and sustainability of the system.

Given the high risk of further fires in these ecosystems, the principles of fire prevention through manipulation of vegetation, should also be an essential part of the strategy and planning in postfire restoration.

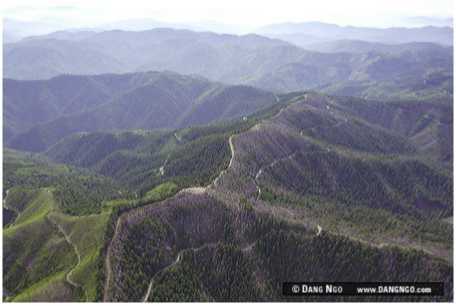
Prior to conducting any restoration activity must take into account:

- Determination of the burned area.
- Characteristics of the affected ecosystems.
- Socio-economic impact assessment.

- Actions planning to be carried out:
  - Emergency action.
  - Forest restoration activities.

Table 7. Recommendations for Restoration Planning Strategy. From Fundacion Banco Santander (2008).

ACTION	RECOMMENDATION
Restoration Objectives  **le.ac.uk**	• Analyse the objectives of forestry management based on the current demand by the society on forest products and services, and taking into account in the planning restoration measures. • Promote the participation of different Special Interest Groups in defining the objectives of the restoration.
Assessment of the Affected Ecosystem and the Fire Characteristics  westinstenv.org	• Define the target or the reference condition of the forest to recover from the type of forest that existed before the fire and potentially corresponds to the area. • Project the restoration based on detailed studies of post fire biotic characteristics, and the resilience of individual species.

Divide the Burned Area in Stands	
 **dipity.com**	• Divide the burned area in stands and identify the needs of intervention in each one, depending on the characteristics of the terrain and the type of vegetation before the fire.
Erosion and Plague Risk Control	
 **americanforests.org**	• Assess the real risks, according to both erosion and plagues caused by wood boring insects in burned tree trunks, which can act as a source of infection for nearby forests. • Projecting the emergency measures according to those risks. Several researches have shown that plague problems occur in pine forest partly affected by fire, rather than in burned forest, where the woodland is very weak.

Natural Regeneration Capacity	
 pc.gc.ca	• Analyse the postfire natural regeneration capacity of the ecosystem. Define different treatments on the affected area according to the recovery capabilities in each stand. • Prioritize revegetation actions on those areas with low probabilities of preservation as well as areas where ecological succession rates are slow.

After a fire, the activities to carry out can be dividing in two phases. 1) **Rehabilitation**, tending to runoff control and soil loss by erosion (immediately after fire), 2) **Restoration**, aims to facilitate restoration (medium and long-term).

3.7.2 Rehabilitation Activities

Immediately after the fire, a list of the tasks to be completed:

- Hydrological study of the area, collecting data about river network, climate, soil, topography and vegetation cover.
- Assessment of hydrologic and erosion risks. The hydrological study should be including: flood peak flows, sheet and rill erosion; photointerpretation and field reconnaissance work; sediment yield prediction (MUSLE/RUSLE3D/USPED model); Identification of potential risk areas.
- Proposal of high priority actions based on all the data gathered in order to prevent soil erosion effects (sediment transport).

Table 8. Postfire Emergency Actions and Recommendations. From Fundacion Banco Santander (2008).

ACTION	RECOMMENDATION
Hydrological Works For Soil Conservation 	• To reduce runoff and soil erosion, Install fascines following contours, perpendicular to the slope inclination, and made from the finest remains of burned wood. This measure is useful in specific areas of moderate or high slope inclination, but its efficiency depends on its construction and correct location.
 camping.de	• Build temporary dams, perpendicular to the channels, in those streams, rivers, rills or gullies, in order to contain the sediments coming from upstream.
 forest.moscowfsl.wsu.edu	• Prescribe the technical characteristics of fascines and temporary dams doing emphasis on the correct and secure fasten to the ground and its height according to the sediment transport rate.

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Implementation of Emergency Work

pc.gc.ca

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- Give priority to awarding the extraction contract of burned wood to accelerate the process of restoration.
- Finalize emergency work before the spring of the year after the fire. This helps seeds to germinate and buds sprout, and maintain the heritage of the burned forest.

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Emergency Seeding of Herbaceous and / or Shrubs

nature.nps.gov

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- Perform aerial seeding of fast-growing native species over degraded hillslopes with high risk of erosion and poor regeneration capacity, in which the construction of fascines is not enough to ensure soil protection.
- Mixing herbaceous and shrub species, in the seeding composition, contributes to soil protection, improves water infiltration, reduces compaction and increases the vegetation recovery in medium and long term.
- Make the seeding during the first autumn after the fire, mainly in Mediterranean climate zones, to maximize chances of survival and give to the plants a longer period for growth and adaptation to the environment.

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Specific activities to implement are:

- Determine flood risk in critical areas.
- Cleaning channels of rivers or streams removing vegetation and sediment.
- Adjust installed culverts on tracks, roads, etc.
- Construction of fascines over steep hillslopes with high risk of erosion.
- Building transverse structures in different areas of the stream network.
- Specific actions to facilitate drainage in critical areas.
- Develop recommendations, related to limiting transit of machinery, for wood extraction process.

Table 9. *Emergency Actions and Recommendations That Should Be Considered During the Early Stages after a Fire. From Fundacion Banco Santander (2008).*

ACTION	RECOMMENDATION
Cutting up and Felling of Trees and Shrubs  forestryforum.com	• Implementing this action only in absence of plague risk and when is planning to build soil protection structures (e.g., Fascines). • In case of plague risk, proceed to cut up and fell in order to maintain and manage representative samples of standing dead wood. This action ensures essential biological processes of the ecosystem (bird perches, decomposers, etc.).

Wood Extraction  blog.mercadovial.com  johnsonmatel.com	• Avoid dragging burnt wood, mainly over fragile soils as loams, clays and sandstones. • Use a tractor forwarder instead of a skidder, or extract the wood through hanging packet to minimize the erosive effects of removing wood mechanically. • Minimize opening and extension of logging routes • Establishment of protection zones along the streams and around sensitive areas (steep slopes, rocks, etc.) where machinery is not allowed. • Perform harvesting before the first spring after the fire, to avoid damaging shoots regeneration. In addition, as a preventive measure against bark beetle infestations, the process of wood extraction should be limited to six or nine months after the fire.
Treatment of Plant Remains  directindustry.com	• In order to facilitate the addition of nutrients to the soil, avoid burning plant remains, such as logs or branches (non-wood forest products) in areas where use of tree chippers is feasible. Burn of large piles of plant remains can produce serious problems to the soil. In addition, residual fuel (firewood) after a fire does not usually present a risk of new fires according its volumetric characteristics and rapid decomposition. • Spread fine remains of wood over the soil surface to reduce the risk of erosion, provide organic matter and protect natural regeneration.

3.7.3 Restoration Activities

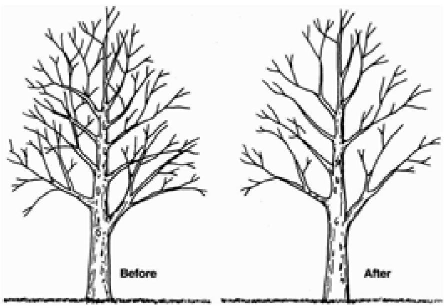
After divided the burned area in stands (Table 7) will be established the activities to carried out in each case according to the species to use for reforestation, soil preparation methods, roads construction and silvicultural practices.

In order to carry out the whole process of restoration, it is important to take some time, after the fire, with the purpose to make better decisions.

The steps and activities to implement in this process are:

- **Regeneration Inventory**: for each homogeneous area, based on the type of regeneration. Assessment of current vegetation, density and regeneration capacity. Each area will be classified according to topographic factors, aspect, and size and presence of shrubs or herbaceous species.
  - Regeneration Type 1-1: Low Regeneration and open-scrub.
  - Regeneration Type 1-2: Low Regeneration and closed-scrub.
  - Regeneration Type 2-1: moderate Regeneration and open-scrub.
  - Regeneration Type 2-2: moderate Regeneration and closed-scrub.
  - Regeneration Type 3-1: High Regeneration and open-scrub.
  - Regeneration Type 3-2: High Regeneration and closed-scrub.
- **Restoration Activities**: The activities to implement will be based on preliminary researches/assessments, and regeneration inventory.

Table 10. Actions and Recommendations for Forest Restoration. From Fundacion Banco Santander (2008).

ACTION	RECOMMENDATIONS
Crown Thinning and Pruning  **forestryimages.org**	• Select the strongest stump shoots of the plants, to favour the development of more mature forest structures (bush and woodlands). The selected shoots will slightly pruned.
Pruning  **nzffa.org.nz**	• Cut out diseased or dead branches after fire, helps to health improvement of remaining forest. This action should be done carefully, since weak individuals have low tolerance to pruning.
Selective Clearing  **furrowlandscaping.com**	• Clearing manually and in a selective way, light-demanding species which can strangle by competition, the regeneration of woodland or scrub. In general, soil conservation favours natural regeneration, however sometimes is necessary to clear around the shoots of some species that have an interest for ensure their growth.

Soil Preparation

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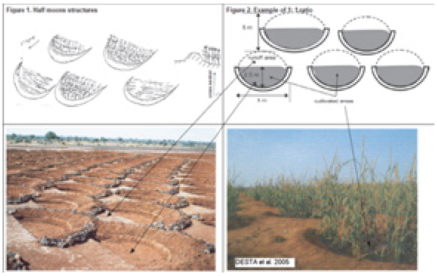

home.agrarian.org

fao.org

- Minimize the mechanized work in soil preparation, in order to avoid negative impacts on the burned soils.
- Avoid removing mid-century terraces used for reforestation, especially if that removal is made following the steepest slope direction, or in areas where regeneration occurs naturally. Regardless to technical justification that motivated the terraces construction, the removal of them, would have serious consequences on soil conservation.
- If the decision is the replacement of species, eucalyptus for example, avoid stump removal with heavy machinery, given the negative impact on the land. This action removes large quantities of soil, and eliminates the ability of the root system to hold this soil. It is recommended to use glyphosate as a non-selective herbicide.
- Desing of microbasins to increase water availability to plants. This technique involves making small pipelines with lateral streams increasing water collect. In addition, reduces the kinetic energy generated on the hillsides, so is advisable that pipelines have a gradient between 45 ° and 90 ° from vertical. This technique does not produce negative impacts on the soil and have an average useful life of approximately 10 years.

The types of actions can be classified into:

- Moderate intervention favouring trees development
- Moderate intervention favouring scrub development
- Minor intervention
- Intervention in ravines
- Intervention in natural forests
- Intervention against plagues and diseases
- Intervention in the road network

Table 11. Actions and Recommendations to Restore Forest Cover. From Fundacion Banco Santander (2008).

ACTION	RECOMMENDATION
Reforestation  parks.ca.gov	• Start reforestation in those stands in which regeneration has not been optimal, either by failure in the quantity or the selected species were not the most appropriate. • Set in each stand the objective of the reforestation, i.e., increasing the density of species (densification) or enhancing the diversity of species (enrichment). • Select species based on the objective of reforestation and the compatibility with the characteristics of the soil after the fire. Define the initial planting density depending on the current condition of the forest.
Sowing  kmle.co.kr	• Select mixed tree species plantation instead of monospecific plantation. This action increase biodiversity and landscape regeneration. • Promote manual sowing, in areas where the introduction of machinery for soil preparation is not recommended, either by the current soil conditions, or by the appearance of natural regeneration.

Finally, after the restoration process is finished, specific monitoring actions must be done for the correct maintenance of the work made and ensuring that the recovery is not altered. In addition, this will contribute to assessing the effectiveness and efficiency of the actions taken.

Table 12. Actions and recommendations for the evaluation and monitoring of restorated areas. From Fundacion Banco Santander (2008).

ACTION	RECOMMENDATION
Restoration M**aintenance Action**	
 bennettconsultingpllc.com	• Evaluate the necessity to carry out maintenance work. Although restoration projects must be designed to maintain themselves, in some cases, like reforestation, may require certain actions such as replacement of trees, primarily during the early stages of the adaptation to the new soil conditions.
Monitoring of Natural Regeneration	
 gov.mb.ca	• In case of the restoration program does not reach optimal levels, it will be necessary to establish a regular monitoring of the post-fire ecosystem.

Evaluation of Implemented Actions	
 ieca.org	• Evaluate the short, medium and long term, the degree of compliance with the restoration objectives by comparing the initial situation after the fire to the situation of the land after the implementation of the corrective actions.

It is important to mention that sometimes, the monitoring stage is not carried out because it was not taking into account in the restoration actions budget. Therefore, it is important to include this item in the general budget.

4 Study Cases. Postfire Treatments Effectiveness

4.1 Post-Fire Treatment Effectiveness and Treatment Performance

Several reports have differentiated "treatment effectiveness" from "treatment performance." Treatment effectiveness will describe how well a treatment meets emergency stabilization objectives. For example, if straw mulch was applied to burned hillslopes to reduce peak flow rates and sediment yields, the treatment effectiveness would be the reduction in those two variables that could be ascribed to the treatment. Measured peak flow rates and sediment yields from equivalent treated and untreated areas would be compared to make that determination. Differences between the treated and untreated areas are generally expressed in percent difference and are often described as the "percent reduction due to treatment". In contrast, treatment performance is related to the materials used in the treatment (for example, thickness of straw stalks and length of wood strands), installation features (for example, percent cover and depth of straw), and changes over time (for example, movement by wind and decay rate). Treatment performance characteristics can affect treatment effectiveness, which is why they are assessed and monitored in addition to treatment effectiveness. However, emergency hillslope treatment effectiveness information (generally, reduction in runoff, peak flows, and/or sediment yields) can be difficult to interpret when combined with measurements of treatment performance.

Although the need to measure treatment effectiveness has gained acceptance, there are limited data to determine if postfire treatments are practical and effective. Field measurements of runoff and/or sediment yields in burned areas require a rapid response research protocol and are generally expensive and labour-intensive. Such studies are challenging to fund and sustain over time. Nonetheless, quantitative treatment effectiveness data influence treatment decisions.

4.2 Hillslope Treatments

Hillslope treatments include grass seeding, contour-felled logs, mulch, and other methods intended to reduce surface runoff and keep postfire soil in place on the hillslope. These treatments are regarded as a first line of defense against postfire sediment movement, preventing subsequent deposition in unwanted areas. Consequently, more research has been published on hillslope treatments than on other methods.

4.2.1 Broadcast Seeding

One of the most common restoration practices is broadcast seeding of grasses, usually from aircraft. Grass seeding after fire for range improvement has been practiced for decades, with the intent to gain useful products from land that will not return to timber production for many years. As an emergency treatment, rapid vegetation establishment has been regarded as the most cost-effective method to promote rapid infiltration of water, keep soil on hillslopes and out of channels and downstream areas. Grasses are particularly desirable for this purpose because their extensive, fibrous root systems increase water infiltration and hold soil in place. Fast-growing non-native species have typically been used. They are inexpensive and readily available in large quantities when an emergency arises.

Legumes are often added to seeding mixes for their ability to increase available nitrogen in the soil after the postfire nutrient flush has been exhausted, aiding the growth of seeded grasses and native vegetation. Seed mixes were refined for particular areas as germination and establishment success were evaluated. Most mixes contained annual grasses to provide quick cover and perennials to establish longer term protection. However, non-native species that persist can delay recovery of native flora and potentially alter local plant diversity. Recently studies have recommended non-reproducing annuals, such as cereal grains or sterile hybrids that provide quick cover and then die out to let native vegetation reoccupy the site.

4.2.2 Conifer Forest

High intensity fire may be outside the range of natural variability for many conifer plant communities that have been subject to fire suppression for the last century. The loss of former understory seed banks due to overgrazing and canopy densification may also reduce the likelihood of rapid regeneration of ground cover after fire. Seeding mixes used in conifer stands often include legumes such as *Trifolium repens* or *Melilotus officinalis* to enhance nitrogen status of the soil. Both annual and perennial grasses may be used in mixes with non-native forage species originally tested for range improvement purposes.

A study examined plant cover and erosion for 3 years after fire in the Black Hills of South Dakota (USA) in an area operationally seeded with a mixture of grasses and legumes. Most of the sediment production occurred in two summer storms shortly after erosion- measuring apparatus was set up. Sediment production was inversely related to plant cover. Summer storm runoff was 50 percent less on plots with high plant and litter cover than on those with sparse cover. Regression analysis showed that the decrease in runoff and sediment production with increasing ground cover leveled off at 60 percent cover, similar to another study results.

Seeded grasses provided greater cover than natural regeneration in a burned area in Oregon (USA). Litter and mulch also developed more rapidly on the seeded sites.

After 4 years, however, all sites had more than 70 percent ground cover. Legume species included in the seeding mix for wildlife forage generally did not survive. Seeded grasses appeared to suppress growth of native shrubs and annual forbs, particularly in the second and third year after fire. Erosion amounted to only 5 t ac-1 (5.5 Mg ha-1) during the first 2 years after fire on seeded sites.

In contrast, another research measured negligible cover produced by seeded species on severely burned plots in Oregon (USA). Total vegetation cover was only 40 percent after 2 years even on lightly burned sites. It suggested that nitrogen fertilization might have improved vegetation growth. Earlier study found that grass vigor decreased 4 years after seeding along forest roads for erosion control, and re-fertilization in year 7 re-invigorated perennial grasses in the plots. Over disturbed firelines, were seeded various grasses and legumes and found that fertilization greatly increased initial cover of most species tested. Fertilization with 45 lb ac-1 (50 kg ha-1) drilled urea significantly increased native plant regrowth, but not production of seeded species, on granitic soil in Idaho (USA).

Seeding and fertilizer treatments were compared on separate watersheds in the Washington Cascades (USA) after a fire swept through the Entiat Experimental Forest. Seeding increased plant cover at the end of the first growing season by about one third, from 5.6 percent on the unseeded watershed to 7.5 to 10.8 percent on the seeded watersheds. Seeded grasses made up 18 to 32 percent of total cover on seeded sites. Nitrate concentration in streams increased immediately after fertilizer application, but subsequently fertilized and unfertilized watersheds had similar stream nitrogen dynamics. Later that summer, record rainfall events caused massive flooding and debris torrents from treated and untreated watersheds alike. In the second year after fire, average total plant cover increased to 16.2 percent on the unseeded watershed and 16.4 to 23 percent on the seeded watersheds. Seeded grasses comprised about 7 percent cover on seeded watersheds. On south-facing slopes, the unseeded watershed had as much or more cover than the seeded ones.

From an erosion standpoint during the first winter after fire, the amount of seeded grass present at the time major storms occur is more important than the amount present at the end of the growing season, when it is usually assessed in studies. In southern Oregon (USA), annual ryegrass seeding and fertilization did not significantly increase plant cover or reduce erosion by early December, when that winter's major storms occurred. The seeded and fertilized plots had significantly less bare ground than the unseeded plots. Erosion was low and not significantly different between treatments, though it trended lower on the seeded plots. The research pointed out that timing of rainfall is critical to both grass establishment and erosion, and that different rainfall patterns could have produced different results from the study.

In contrast, grass seeding plus fertilizer did not significantly increase total plant cover during the first 5 years after a northern Sierra Nevada fire (USA). Seeded grass cover did not exceed 10 percent until 3 years after the fire, when total cover on unseeded plots was greater than 50 percent. There was no difference in erosion between the seeded and unseeded watersheds during the first 2 years after fire. Another study also found that total plant cover did not differ between seeded and unseeded plots for 5 years after an Idaho fire (USA). Seeded plots had lower cover of native species.

Several species commonly used for postfire seeding, because of their rapid growth and wide adaptability, have been found to be strongly competitive with conifer seedlings in experimental plots. Orchardgrass *(Dactylis glomerata)*, perennial ryegrass *(Lolium perenne)*, and timothy *(Phleum pratense)* reduced growth of ponderosa pine seedlings in tests conducted in California (USA). Orchardgrass and crested wheatgrass *(Agropyron desertorum)* reduced ponderosa pine growth in Arizona (USA). Field studies on aerial seeded sites in California found low pine seedling densities on most plots with annual ryegrass cover higher than 40 percent.

A research reported significantly lower survival of planted sugar pine *(Pinus lambertiana)* seedlings in plots heavily seeded with annual ryegrass than in unseeded controls during the first postfire year in southern Oregon (USA). Soil moisture was significantly lower and pine seedlings showed significantly greater water stress in the seeded plots. Ryegrass cover was 49 percent when tree seedlings were planted and 85 percent by mid-summer, while total plant cover was only 24 percent at mid-summer on the control plots. The next summer, a second group of planted pine seedlings had significantly greater survival and lower water stress on seeded plots than on controls. By then, dead ryegrass formed a dense mulch on the seeded plots, but no live grass was found. Native shrub cover was significantly greater on the unseeded plots the second year and soil moisture was lower. Ryegrass thus acted as a detrimental competitor to tree seedlings the first year after fire, but provided a beneficial mulch and reduced competition from woody plants the second year. The study also suggested that seeded ryegrass could benefit planted conifer seedlings if it suppressed woody competitors and could itself later be controlled. In their study, however, live ryegrass cover was exceptionally high in many plots during the second year after fire.

Measuring erosion and runoff is expensive, complex, and labor-intensive, and few researchers have done it. Such research is necessary to determine if seeded grasses control erosion better than natural regeneration. Another goal of postfire grass seeding on timber sites, soil fertility retention, does not appear to have been investigated. Grass establishment can clearly interfere with native plant growth, and grass varieties that will suppress native shrubs but not conifer seedlings have not yet been developed. The impacts of recent choices for rehabilitation seeding, including native grasses and cereal grains, on natural and planted regeneration in forest lands have not been studied extensively.

Another study found that rainfall intensity explained more than 80 percent of the variability in sediment yields. After the 2000 Bobcat Fire in Colorado (USA), a single storm with 30 min rainfall intensity of 42 mm hr-1 resulted in 370 kg ha-1 and 950 kg ha-1 sediment yields, on treated (erosion-control with contour log felling, grass seeding, and mulching) and untreated watersheds, respectively.

4.2.3 Mulch

Mulch is material spread over the soil surface to protect it from raindrop impact. Straw mulch applied at a rate of 0.9 t ac-1 (2 Mg ha-1) significantly reduced sediment yield on burned pine-shrub forest in Spain over an 18-month period with 46 rainfall events. Sediment production was 0.08 to 1.3 t ac-1 (0.18 to 2.92 Mg ha-1) on unmulched plots but only 0.04 to 0.08 t ac-1 (0.09 to 0.18 Mg ha-1) on mulched plots. Other research, tested straw mulch laid down at four rates—0.5, 1, 1.5, and 4 t ac-1 (1.1, 2.2, 3.4, and 9.0 Mg ha-1)—against jute excelsior, and paper for erosion control. Straw was the most cost-effective mulch, superior in protection to hydraulic mulches and comparable to expensive fabrics. Excelsior was less effective but better than paper strip synthetic yarn. The best erosion control came from jute applied over 1.5 t ac-1 (3.4 Mg ha-1) straw. Other researchers studied the use of wheat straw mulch on the 1987 South Fork of the Trinity River fire, Shasta-Trinity National Forest in California (USA). Wheat straw mulch was applied to fill slopes adjacent to perennial streams, firelines, and areas of extreme erosion hazard. Mulch applied at rates of 2 t ac- 1 (4.5 Mg ha-1), or 1 t ac- 1 (2.2 Mg ha-1) on larger areas, reduced erosion 6 to 10 yd3 ac-1 (11 to 19 m3 ha-1). They considered mulching to be highly effective in controlling erosion. Another study examined the effects of straw mulching at rates of 0.9,1,8, 2.7, and 3.6 t ac- 1 (2,4,6, and 8 Mg ha-1) on 5 to 9 percent slopes. Soil loss at 0.9 t ac-1 (2 Mg ha-1) mulch was significantly greater (1.4 t ac-1, 3.16 Mg ha-1 of soil) than at 1.8 t ac-1 (4 Mg ha-1) mulch (0.9 t ac-1, 1.81 Mg ha-1 of soil loss). Above 1.8 t ac-1 (4 Mg ha-1) mulch there was no further reduction in soil loss .

4.2.4 Contour-Felled Logs

This treatment involves felling logs on burned-over hillsides and laying them on the ground along the slope contour, providing mechanical barriers to water flow, promoting infiltration and reducing sediment movement; the barriers can also trap sediment (Figures 9 and 10). The terms "log erosion barriers" or "log terracettes" are often used when the logs are staked in place and filled behind. Logs were contour-felled on 22 ac (9 ha) of the 1979 Bridge Creek Fire, Deschutes National Forest in Oregon (USA). Trees 6 to 12 in (150-300 mm) d.b.h. (Diameter Breast Height) were placed and secured on slopes up to 50 percent at intervals of 10 to 20 ft (3 to 6 m). Logs were staked and holes underneath were filled. After the first storm event, about 63 percent of the contour-felled logs were judged effective in trapping sediment. The remainder were either partially effective or did not receive flow. Nearly 60 percent of the storage space behind contour-felled logs was full to capacity, 30 percent was half-full, and 10 percent had insignificant deposition. Common failures were flow under the log and not placing the logs on contour (more than 25° off contour caused trap efficiency to decrease to 20 percent). Over 1,600 yd3 (1,225 m3) of material was estimated trapped behind contour-felled logs on the 22 ac, or about 73 yd3 ac-1 (135 m3 ha-1).

Figure 7. Example of treatment involving felling logs on burned-over hillsides (source: ext. colostate.edu AND watercenter.montana.edu)

Only 1 yd3 (0.7 m3) of sediment was deposited in the intake pond for a municipal water supply below. Another study monitored contour-felling on the 1987 South Fork Trinity River fires, Shasta-Trinity National Forest in California (USA). The treatment was applied to 200 ac (80 ha) within a 50,000 ac (20,240 ha) burned area. Trees <10 in (250 mm) d.b.h. spaced 15 to 20 ft (4.5 to 6 m) apart were felled at rate of 80-100 trees ac-1 (200250 trees ha-1). The contour-felled logs trapped 0 to 0.07 yd3 (0 to 0.05 m3) of soil per log, retaining 1.6 to 6.7 yd3 ac-1 (3 to 13 m3 ha-1) of soil onsite. The study considered sediment trapping efficiency low and the cost high for this treatment.

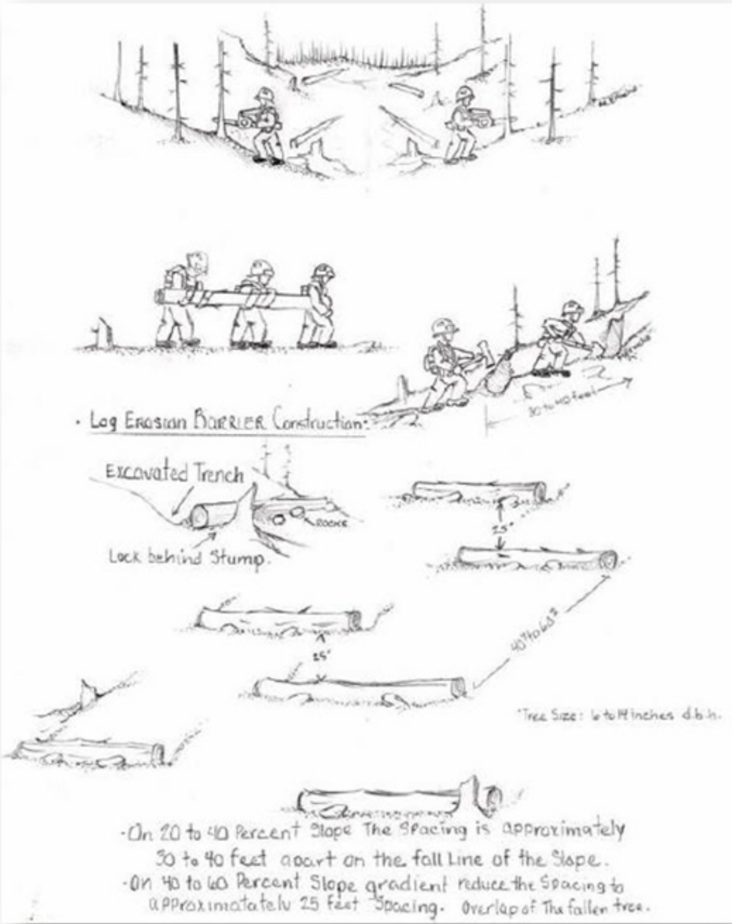

Figure 8. Guidelines for felling logs treatment (www.fws.gov/fire/ifcc/esr/Treatments/contour-fellingi.htm)

4.2.5 Contour Trenching

Contour trenches have been used as a treatment to reduce erosion and permit revegetation of fire-damaged watersheds. Although they do increase infiltration rates, the amounts are dependent on soils and geology. Contour trenches can significantly improve revegetation by trapping more snow, but they do not affect water yield to any appreciable extent. This treatment can be effective in altering the hydrologic response from short duration, high intensity storms typical of summer thunderstorms, but does not significantly change the peak flows of low intensity, long duration rainfall events. A study noted that contour trenching in the sagebrush *(Artemisia* spp.) portion (upper 15 percent with the harshest sites) of a watershed in central Utah (USA) did not significantly change stream flow and storm flow patterns. Another reported on the use of contour trenching on recently burned steep slopes (40 to 50 percent) with clay loam soils in pine stands of the Philippines. Contour trenching reduced sediment yield by over 80 percent, from 28 to 5 t ac-1 (63 to 12 Mg ha-1).

4.3 Channel Treatments

Channel treatments are implemented to modify sediment and water movement in ephemeral or small-order channels, to prevent flooding and debris torrents that may affect downstream values at risk. Some in-channel structures slow water flow and allow sediment to settle out; sediment will later be released gradually as the structure decays. Channel clearing is done to remove large objects that could become mobilized in a flood. Much less information has been published on channel treatments than on hillslope methods.

4.3.1 Straw Bale Check Dams

A reported was made based on the results of installing 1300 straw bale check dams after the 1987 South Fork Trinity River fires, Shasta-Trinity National Forest, California (USA). Most dams were constructed with five bales (Figures 12 and 13). About 13 percent of the straw bale check dams failed due to piping under or between bales or undercutting of the central bale. Each dam stored an average 1.1 yd3 (0.8 m3) of sediment. The researchers felt that filter fabric on the upside of each dam and a spillway apron would have increased effectiveness. They considered straw bale check dams easy to install and highly effective when they did not fail. Other study evaluated the effectiveness of straw bales on sediment retention after the Oakland Hills fire. About 5000 bales were installed in 440 straw bale check dams and 100 hillslope barriers. Three months after installation, 43 to 46 percent of the check dams were functioning. This decreased to 37 to 43 percent by 4.5 months, at which time 9 percent were side cut, 22 percent were undercut, 30 percent had moved, 24 percent were filled, 12 percent were unfilled, and 3 percent were filled but cut. Sediment storage amounted to 55 yd3 (42 m3) behind straw bale check dams and another 122 yd3 (93 m3) on an alluvial fan.

Other researchers recommended that the drainage area for straw bale check dams be kept to less than 20 ac (8 ha). Bales usually last less than 3 months, flow should not be greater than 11 cfs (0.3 m3 s-1), and bales should be removed when sediment depth upstream is one-half of bale height. More damage can result from failed barriers than if no barrier were installed.

4.3.2 Log Check Dams

Logs 12 to 18 in (300 to 450 mm) diameter were used to build 14 log check dams that retained from 1.5 to 93 yd3 (mean 29 yd3/1.1 to 71 m3, mean 22 m3) of sediment after the 1987 South Fork Trinity River fires on the Shasta-Trinity National Forest, California (USA). While log check dams have a high effectiveness rating and 15 to 30 years life expectancy, they are costly to install (Figure9).

Figure 9. Several examples of log check dams (Source: fs.usda.gov and Tardio, G.)

4.3.3 Rock Dams and Rock Cage Dams (Gabions)

Properly designed and installed rock check dams and rock cage (gabion) dams are capable of halting gully development on fire-disturbed watersheds, and reducing sediment yields by 60 percent or more. Although these structures are relatively expensive, they can be used in conjunction with vegetation treatments to reduce erosion by 80 percent and suspended sediment concentrations by 95 percent (Figure 10). While vegetation treatments such as grassed waterways and rock check dams are less expensive, their maintenance costs are considerably greater. Check dams constructed in Taiwan watersheds with annual sediment yields of 10 to 30 yd-3 ac (19 to 57 m3 ha-1) filled within 2 to 3 years. Sediment yield rates decreased upstream of the check dams, but were offset by increased scouring downstream.

Figure 10. Image of a rock cage dams installed in Guadalajara, Spain (source: Gimenez s., M)

4.4 Road Treatments

Road treatments consist of a variety of practices aimed at increasing the water and sediment processing capabilities of roads and road structures, such as culverts and bridges, in order to prevent large cut-and-fill failures and the movement of sediment downstream (Figure 11). The functionality of the road drainage system is not affected by fire, but the burned-over watershed can affect the functionality of that system. Road treatments include outsloping, gravel on the running surface, rocks in ditch, culvert removal, culvert upgrading, overflows, armored stream crossings, rolling dips, and water bars. The treatments are not meant to retain water and sediment, but rather to manage water's erosive force. Trash racks and storm patrols are aimed at preventing culvert blockages due to organic debris, which could result in road failure that would increase downstream flood or sediment damage (Figure 16).

Furniss and others (1998) developed an excellent analysis of factors contributing to the failure of culverted stream crossings. Stream crossings are very important, as 80 to 90 percent of fluvial hillslope erosion in wildlands can be traced to road fill failures and diversions of road-stream crossings. Since it is impossible to design and build all stream crossings to withstand extreme stormflows, they recommended increasing crossing capacity and designing to minimize the consequences of culvert exceedence as the best approaches for forest road stream crossings.

Figure 11. Images of road treatments in Las Rozas de Madrid, Spain (Source: Garcia R. J.L.)

4.5 Postfire Restoration. A Spanish Case

4.5.1 Forest fires in Sierra Mariola National Park (Buixcarró Hill-province of Alicante) between 1985 and 1994

Introduction

In 1985 a forest fire burned 110 hectares of Buixcarró farm, located in the Sierra Mariola National Park, Alcoy, Alicante. Nine years later, in 1994, there were multiple forest fires in the community of Valencia, destroying a total of 138,000 hectares. In this year, a negligence caused a huge fire that affected 15,000 hectares. 3,800 of those 15,000 correspond to Sierra de Mariola and 420 to Buixcarró farm.

Forest condition before the fire

Before the fire the area was characterized by significant heterogeneity due to the existence of many terraces for cultivation and areas with different exposure. The zones of shades were characterized by the existence of mature sclerophyll forests with a developed understory, traditionally utilized for domestic use (firewood).

The zones of sunlight were characterized by coniferous forests like Aleppo pine and heliophilous scrub, dominated by esparto and rosemary.

Restoration plan: Emergency actions implemented

Approval of a plan restricting big game hunting for adequate control of the population of herbivores, in order not to exceed the land carrying capacity.

In order to facilitate the addition of nutrients to the soil, plants remains were chipped and animal traction was used for wood extraction, avoiding the proliferation of drillers and leaving at least 2 percent of the standing burned trees with low degradation, to ensure essential biological processes of the ecosystem (bird perches, decomposers, etc.).

Forestry Management Plan 2003-2013: Depending on land characteristics and the priority of intervention, establishing a restoration plan for the next ten years. Until 2008, 120 hectares were restored of 300 hectares identified with intervention needs.

Measures to encourage natural regeneration

- Selective bush clearings, around regenerated trees and species like junipers, hawthorns or kermes.
- Clearing, pruning and crown thinning to achieve viability in regeneration densities. In stands with densities of 6,000 to 8,000 trees per hectare, practiced clearing to reach densities of 800 to 1,000 trees per hectare, with the purpose to later select those trees with the fastest growing or better adaptation to the environment.
- Use of beekeeping with the purpose of promoting pollination and increase the production of viable seeds.

Reforestation

Base on the fact that the ecosystem has a high regeneration capacity, reforestation only be necessary to increase biodiversity, mainly of native species that produce berries such as strawberry. In addition, in those areas where densities of regeneration have been little or no action due to repeated series of fires, were reforested with oaks and junipers.

Evaluation of restoration actions

The implemented actions have been successfully both improving the viability and productivity of regeneration, and for the species diversification, which contributes to improving trophic availability for many animal species.

ACTIONS	INITIAL STATE	FINAL STATE
• Reintroduction of wild rabbits (Construction of nursery, recapture and translocation, revaccination, installation and maintenance of feeders and drinkers, disinfection of refuges).	• Previously to the reintroduction plan, the estimated population of wild rabbits (Oryctolagus cuniculus) in the property was 30-50 individuals.	• After the action plan, the estimated population of wild rabbits (Oryctolagus cuniculus) in the property was 250-320 individuals
• Hunting management of the population of mouflons (Ovis musimon). Estimated carrying capacity on the property: 150 individuals.	• The estimated population of mouflons (Ovis musimon) in the property was 160-180 individuals.	• After 2006 the estimated population of mouflons (Ovis musimon) in the property was 150-170 individuals.
Installation of feeders and drinkers for small wild game, maintenance of minimum ecological levels at water sources and pasture-seeding in the abandoned fields.	The estimated population of partridges (Alectoris rufa) in the property was 250-280 individuals.	After 2006 the estimated population of partridges (Alectoris rufa) in the property was 480-550 individuals.

Silvicultural treatments (Selective Clearing, Crown Thinning, Pruning, removal of burned trees, etc.).	Important regeneration of slow growing species. Treated area until 2007: 118 ha.	Increase of average diameter of oaks: • In treated Area: 22% • In untreated area: 10% • Increase of trees height: • In treated Area: 45 cm • In untreated: 28 cm

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ANNEX I. DEFINITIONS

Keeping in mind that the literature of watershed rehabilitation contains many terms from hydrological, ecological and fire science disciplines is necessary, for clarity, defined the most common terms.

Aerial Seeding: See Seeding.

Allelopathy: Inhibition of competing plant growth by exudation of naturally produced, phytotoxic biochemicals.

Annuals (Annual Plants): Plant that completes its growth and life cycle in one growing season.

Ash-bed Effect: Stimulation of plant growth caused by the sudden availability of fire-mineralized plant nutrients contained in ash residues from a fire.

Armored Ford Crossing: Road crossing of a perennial or ephemeral stream at or near the existing cross-section gradient that is generally constructed of large rocks capable of bearing the weight of the vehicles and resisting transport by the stream.

Armoring: Protective covering, such as rocks, vegetation or engineering materials used to protect stream banks, fill or cut slopes, or drainage structure outflows from flowing water.

Best Management Practices: Preferred activities which minimize impacts on soil, water, and other resources.

Broadcast seeding: See Seeding.

Burn Severity: Qualitative and quantitative measure of the effects of fire onsite resources such as soil and vegetation. Fire intensity contributes to severity but does not alone define it.

Chaparral: Shrub-dominated evergreen vegetation type abundant in low- to mid-level elevations in California and the Southwest.

Channel Clearing: Removal of woody debris from channels by heavy equipment or cable yarding.

Channel Loading: Sediment inputs into ephemeral or perennial stream channels.

Check Dam: Small structure in zero or first order channels made of rocks, logs, plant materials, or geotextile fabric designed to stabilize the channel gradient and store a small amount of sediment.

Contour-Felled Logs: System for detaining runoff and sediment on slopes by felling standing timber (snags) along the contour, delimbing and anchoring the logs, and backfilling to create small detention basins. Also known as contour- felling, contour log terraces, log erosion barriers (LEBs). In some regions, contour-felling describes only felling the standing timber in the direction of the contour but not anchoring or backfilling.

Contour Furrowing: See Contour Trenching.

Contour Trenching: Construction of trenches on slope contours to detain water and sediment transported by water or gravity downslope generally constructed with light equipment. These are also known as contour terraces or contour furrowing.

Cross Drain: A ditch relief culvert or other structure or shaping of a road surface designed to capture and remove surface water flow.

Culvert Overflow: Specially designed sections of roadway that allow for overflow of relief culverts or cross-drain culverts without compromising the integrity of the road surface.

Culvert Riser: Vertical extension of culvert on the uphill side to create a small pond for detaining sediment.

Culvert Upgrading: Replacing existing culverts with large diameter ones. May also include armouring of inlet and outlet areas.

Debris Avalanche: Mass failure of variably sized slope segments characterized by the rapid downhill movement of soil and underlying geologic parent material.

Debris Basin: Specially engineered and constructed basin for storing large amounts of sediment moving in an ephemeral stream channel.

Debris Clearing: See Channel Clearing.

Design Storm: Estimate of rainfall amount and duration over a particular drainage area. Often used in conjunction with the design storm return period, which is the average number of years within which a given hydrological event is equalled or exceeded (i.e., 5-year return period).

Ditch Maintenance: Various maintenance activities to maintain or restore the capacity of ditches to transport water. Activities include sediment and woody debris removal, reshaping, and armouring.

Dry Ravel: Downhill movement of loose soil and rock material under the influence of gravity and freeze-thaw processes.

Ephemeral Stream or Channel: Drainage way which carries surface water flow only after storm events or snow melt.

Energy Dissipater: Rock, concrete, or impervious material structure which absorbs and reduces the impact of falling water.

Erosion: Detachment and transport of mineral soil particles by water, wind, or gravity

Fire Intensity: Rate at which fire is producing thermal energy in the fuel-climate environment in terms of temperature, heat yield per unit mass of fuel, and heat load per unit area.

Fire Severity: See Burn Severity.

Forb: Herbaceous plant other than grasses or grass like plants.

Gabion: A woven galvanized wire basket sometimes lined with geotextiles and filled with rock, stacked or placed to form an erosion resistant structure.

Geotextile (Geowebbing): Fabric, mesh, net, etc. made of woven synthetic or natural materials used to separate soil from engineering material (rocks) and add strength to a structure.

Grade Stabilizer: Structure made of rocks, logs, or plant material installed in ephemeral channels at the grade of the channel to prevent downcutting.

Ground Seeding: See Seeding.

Hand Trenching: Contour trenching done manually rather than mechanically.

Hydrophobic Soil: See Water Repellency.

In-channel Felling: Felling of snags and trees into stream channel to provide additional woody debris for trapping sediment.

Infiltration: Movement of rainfall into litter and the soil mantle.

Lateral Keying: Construction or insertion of log or rock check dam 1.5 to 3 ft (0.4 to 1.0 m) into stream or ephemeral channel banks.

Log Check Dam: See Check Dam.

Log Erosion Barriers (LEBS): see Contour-Felled Logs.

Log Terraces: See Contour-Felled Logs.

Mass Wasting: Movement of large amounts of soil and geologic material downslope by debris avalanches, soil creep, or rotational slumps.

Mg ha-1: Metric ton per hectare or megagram per hectare, equivalent to 0.45 tons per acre (0.45 t ac-1).

Monitoring: The collection of information to determine effects of resource management or specific treatments, used to identify changing conditions or needs.

Monitoring, Compliance: Monitoring done to assure compliance with Best Management Practices.

Monitoring, Effectiveness: Monitoring done to determine the effectiveness of a treatment in accomplishing the desired effect.

Monitoring, Implementation: Monitoring done to verify installation of treatment was accomplished as specified in installation instruction documents.

Mulch: Shredded woody organic material, grass, or grain stalks applied to the soil surface to protect mineral soil from raindrop impact and overland flow.

Mychorrhizae: Fungi which symbiotically function with plant roots to take up water and nutrients, thereby greatly expanding plant root systems.

Outsloping: Shaping a road surface to deflect water perpendicular to the travelled way rather than parallel to it.

Peakflow: Maximum flow during storm or snow melt runoff for a given channel.

Perennials (Perennial Plants): Plants that continue to grow from one growing season to the next.

Perennial Stream and Channel: Drainage ways in which flow persists throughout the year with no dry periods.

Plant Cover: Percentage of the ground surface area occupied by living plants.

Plant Species Richness: Number of plant species per unit area.

Ravel: See Dry Ravel.

Re-bar: Steel reinforcing bar, available in various diameters, used to strengthen concrete or anchor straw bales and wattles.

Regreen: Commercially available sterile wheatgrass hybrid used to stabilize slopes immediately after a fire but not interfere with subsequent native plant recovery.

Relief Culvert: Conduit buried beneath road surface to relieve drainage in longitudinal ditch at the toe of a cut slope.

Return Interval: Probabilistic interval for recurrence (1, 2, 5, 10, 20, 50, 100 years etc.) of storm flow, rainfall amount or rainfall intensity.

Rill: Concentrated water flow path, generally formed on the surface of bare soil.

Riparian Area: Area alongside perennial or ephemeral stream that is influenced by the presence of shallow groundwater.

Ripping: See Tilling.

Risk: The chance of failure.

Rock Cage Dam: See Gabion or Check Dam.

Rolling Dip: Grade reversal designed into a road to move water off of short slope section rather than down long segment.

Rotational Slump: Slope failure characterized rotation of the soil mass to a lower angle of repose.

Runoff: Movement of water across surface areas of a watershed during rainfall or snowmelt events.

Sediment: Deposition of soil eroded and transported from locations higher in the watershed.

Sedimentation: Deposition of water, wind, or gravity entrained soil and sediment in surface depressions, side slopes, channel bottoms, channel banks, alluvial flats, terraces, fans, lake bottoms, etc.

Sediment Trap Efficiency: Percent of contour-felled log length showing accumulated sediment relative to available length of log. Or percent of sediment accumulated behind logs relative to available storage capacity of the logs. Or percent of sediment stored behind logs relative to sediment that was not trapped and moved to the base of a hillslope.

Sediment Yield (Production): Amount of sediment loss off of unit area over unit time period usually expressed as t ac-1 yr-1 or t ha-1 yr-1.

Seeding: Application of plant seed to slopes by aircraft (Aerial Seeding or Broadcast Seeding), or by ground equipment or manually (Ground Seeding).

Silt Fence: Finely woven fabric material used to detain water and sediments.

Slash Spreading: Dispersal of accumulations of branches and foliage over wider areas.

Slope Creep: Slow, downhill movement of soil material under the influence of gravity.

Soil/Site Productivity: Capability of a soil type or site to produce plant and animal biomass in a given amount of time.

Soil Wettability: See Water Repellency.

Storm Duration: Length of time that a precipitation event lasts.

Storm Magnitude: Relative size of precipitation event.

Storm Patrol: Checking and cleaning culvert inlets to prevent blockage during storm runoff.

Straw Bale Check dam: Check dam made of straw or hay bales often stacked to provide additional storage capacity. Designed to store sediment and/or prevent downcutting.

Straw Wattle: Woven mesh netting (1 ft diameter by 6 to 20 ft in length, 0.3 m diameter by 1.8 m to 6.1 m in length) filled with straw or hay and sometimes seed mixes, used to trap sediment and promote infiltration.

Stream Bank Armouring: Reinforcing of streambank with rock, concrete, or other material to reduce bank cutting and erosion.

Streamflow: Movement of water in a drainage channel.

Temporary Fencing: Fencing installed on a grazing allotment or other unit to keep cattle or native ungulates out of burned area.

Terracette: See Contour-Felled Logs.

Tilling: Mechanical turning of the soil with a plow or ripping device. Often used to promote soil infiltration by breaking up water repellent soil layers.

Trash Rack: Barrier placed upstream of a culvert to prevent woody debris from becoming jammed into the inlet. Ungulate: Herbivorous animals with hooves, e.g., cow, elk, deer, horses, etc.

Water Bar: Combination of ditch and berm installed perpendicular or skew to road or trail centerline to facilitate drainage of surface water; sometimes nondriveable and used to close a road.

Water Repellency: Tendency of soil to form a hydro- phobic (water resistant) layer during fire that subsequently prevents infiltration and percolation of water into the soil mantle.

Watershed: An area or region bounded peripherally by ridges or divides such that all precipitation falling in the area contributes to its watercourse.

Water Yield: Total runoff from a drainage basin.

Chapter

7

Polluted Soils Restoration

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Chapter 7

Polluted Soils Restoration

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1 Background for effective remediation technologies

1.1 Definition

Any unwanted substance introduced into the environment is referred to as a 'contaminant'. Deleterious effects or damages by the contaminants lead to 'pollution', a process by which a resource (natural or man-made) is rendered unfit for use, more often than not, by humans. Pollutants are present since time immemorial, and life on the earth as we define now has always evolved amongst them. With pollutant analogues from geothermal and volcanic activities, comets, and space dust which are about 100 t of organic dust per day, the earth is forever a polluted planet. Relative to the pre-industrialization era, industrialization and intensive use of chemical substances such as petroleum oil, hydrocarbons (e.g., aliphatic, aromatic, polycyclic aromatic hydrocarbons (PAHs), BTEX (benzene, toluene, ethylbenzene, and xylenes), chlorinated hydrocarbons like polychlorinated biphenyls (PCBs), trichloroethylene (TCE), and perchloroethylene, nitroaromatic compounds, organophosphorus compounds) solvents, pesticides, and heavy metals are contributing to environmental pollution. Large-scale pollution due to man-made chemical substances and to some extent by natural substances is of global concern now. Seepage and run-offs due to the mobile nature, and continuous cycling of volatilization and condensation of many organic chemicals such as pesticides have even led to their presence in rain, fog and snow. Every year, about 1.7 to 8.8 million metric tons of oil is released into the world's water. More than 90% of this oil pollution is directly related to accidents due to human failures and activities including deliberate waste disposal.

PAHs are present at levels varying from 1 μg to 300 g kg^{-1} soil, depending on the sources of contamination like combustion of fossil fuels, gasification and liquefaction of coal, incineration of wastes, and wood treatment processes (Bamforth and Singleton, 2005). Incomplete combustion of organic substances gives out about 100 different PAHs which are the ubiquitous pollutants. Except for a few PAHs used in medicines, dyes, plastics and pesticides, they are rarely of industrial use (US EPA, 1998). Some PAHs and their epoxides are highly toxic, and mutagenic even to microorganisms. About six specific PAHs are listed among the top 126 priority pollutants by the US Environmental Protection Agency. PCBs, used in hydraulic fluids, plasticizers, adhesives, lubricants, flame retardants and dielectric fluids in transformers are toxic, carcinogenic, and degrade slowly. Polychlorinated dibenzodioxins and dibenzofurans are recalcitrant chemicals and some of the congeners with lateral chlorine substitutions at positions 2,3,7 and 8 are carcinogenic to humans (Kaiser, 2000). Many solvents such as TCE and carbon tetrachloride pollute the environments due to large-scale industrial production and anthropogenic uses. Pesticides are regularly used in agricultural- and public health-programs worldwide. In many cases, the environmental effects of these chemical substances outweigh the benefits they accrue to humans and necessitate the need of their degradation after the intended uses.

The microbial transformation may be driven by energy needs, or a need to detoxify the pollutants, or may be fortuitous in nature (cometabolism). Because of the ubiquitous nature of microorganisms, their numbers and large biomass relative to other living organisms in the earth (Curtis et al., 2002), wider diversity and capabilities in their catalytic mechanisms (Chen et al., 1999 and Paul et al., 2005), and their ability to function even in the absence of oxygen and other extreme conditions (Mishra et al., 2001 and Watanabe, 2001), the search for pollutant-degrading microorganisms, understanding their genetics and biochemistry, and developing methods for their application in the field have become an important human endeavor. The recent advances in metagenomics and whole genome sequencing have opened up new avenues for searching the novel pollutant degradative genes and their regulatory elements from both culturable and non-culturable microorganisms from the environment (Golyshin et al., 2003 and Zhao and Poh, 2008). Compared to other living organisms which can degrade organic pollutants as well as the cost-intensive physical and chemical methods for the cleanup, microorganisms are preferred agents. Their capabilities to degrade organic chemical compounds can be made use of to attenuate the polluted sites.

Environmental remediation deals with the removal of pollution or contaminants from environment (mostly from soil, groundwater, sediment or surface water) for the general protection of human health and the environment or from a industrial site intended for restoration. Remediation is generally subject to regulatory requirements, and also can be based on assessments of human health and ecological risks where no legislated standards exist or where standards are advisory.

In the USA the most comprehensive set of Preliminary Remediation Goals (PRGs) is from the Environmental Protection Agency (EPA) Region 9. A set of standards used in Europe exists and is often called the Dutch standards. The European Union is rapidly moving towards Europe-wide standards, although most of the industrialised nations in Europe have their own standards at present. In Canada, most standards for remediation are set by the provinces individually, but the Canadian Council of Ministers of the Environment provides guidance at a federal level in the form of the Canadian Environmental Quality Guidelines and the Canada-Wide Standards (Canada-Wide Standard for Petroleum Hydrocarbons in Soil).

Once a site is suspected of being contaminated there is a need to assess the contamination. Often the assessment begins with preparation of relevant documents. The historical use of the site and the materials used and produced on site will guide the assessment strategy and type of sampling and chemical analysis to be done. Often nearby sites owned by the same company or which are nearby and have been reclaimed, levelled or filled are also contaminated even where the current land use seems innocuous. For example, a car park may have been levelled by using contaminated waste in the fill. Also important is to consider off site contamination of nearby sites often through decades of emissions to soil, groundwater, and air. Ceiling dust, topsoil, surface and groundwater of nearby properties should also be tested, both before and after any remediation. This is a controversial step as:

1. No one wants to have to pay for the clean up of the site;

2. If nearby properties are found to be contaminated it may have to be noted on their property title, potentially affecting the value;

3. No one wants to pay for the cost of assessment.

In the US there has been a mechanism for taxing polluting industries to form a Superfund to remediate abandoned sites, or to litigate to force corporations to remediate their contaminated sites. Other countries have other mechanisms and commonly sites are rezoned to "higher" uses such as high density housing, to give the land a higher value so that after deducting clean up costs there is still an incentive for a developer to purchase the land, clean it up, redevelop it and sell it.

There are several tools for mapping these sites and which allow the user to view additional information. One such tool is TOXMAP, a Geographic Information System (GIS) from the Division of Specialized Information Services of the United States National Library of Medicine (NLM) that uses maps of the United States to help users visually explore data from the United States Environmental Protection Agency's (EPA) Superfund and Toxics Release Inventory programs.

1.2 Participatory approach in community consultation

In preparation for any significant remediation there should be extensive community consultation. The proponent should both present information to and seek information from the community. The proponent needs to learn about "sensitive" future uses like childcare, schools, hospitals, and playgrounds as well as community concerns and interests information. Consultation should be open, on a group basis so that each member of the community is informed about issues they may not have individually thought about. An independent chairperson acceptable to both the proponent and the community should be engaged (at proponent expense if a fee is required). Minutes of meetings including questions asked and the answers to them and copies of presentations by the proponent should be available both on the internet and at a local library (even a school library) or community centre.

1.3 Health risk

Incremental health risk is the increased risk that a receptor (normally a human being living nearby) will face from (the lack of) a remediation project. The use of incremental health risk is based on carcinogenic and other (e.g., mutagenic, teratogenic) effects and often involves value judgements about the acceptable projected rate of increase in cancer. In some jurisdictions this is 1 in 1,000,000 but in other jurisdictions the acceptable projected rate of increase is 1 in 100,000. A relatively small incremental health risk from a single project is not of much comfort if the area already has a relatively high health risk from other operations like incinerators or other emissions, or if other projects exist at the same time causing a greater cumulative risk or an unacceptably high total risk. An analogy often used by remediators is to compare the risk of the remediation on nearby residents to the risks of death through car accidents or tobacco smoking.

1.4 Emissions standards

Standards are set for the levels of dust, noise, odour, emissions to air and groundwater, and discharge to sewers or waterways of all chemicals of concern or chemicals likely to be produced during the remediation by processing of the contaminants. These are compared against both natural background levels in the area and standards for areas zoned as nearby areas are zoned and against standards used in other recent remediations. Just because the emission is emanating from an area zoned industrial does not mean that in a nearby residential area there should be permitted any exceedances of the appropriate residential standards.

Monitoring for compliance against each standards is critical to ensure that exceedances are detected and reported both to authorities and the local community.

Enforcement is necessary to ensure that continued or significant breaches result in fines or even a jail sentence for the polluter.

Penalties must be significant as otherwise fines are treated as a normal expense of doing business. Compliance must be cheaper than to have continuous breaches.

1.5 Transport and emergency safety assessment

Assessment should be made of the risks of operations, transporting contaminated material, disposal of waste which may be contaminated including workers' clothes, and a formal emergency response plan should be developed. Every worker and visitor entering the site should have a safety induction personalised to their involvement with the site.

1.6 Impacts of funding

The rezoning is often resisted by local communities and local government because of the adverse effects on the local amenity of the remediation and the new development. The main impacts during remediation are noise, dust, odour and incremental health risk. Then there is the noise, dust and traffic of developments. Then there is the impact on local traffic, schools, playing fields, and other public facilities of the often vastly increased local population.

2 Types of remediation technologies for soils and groundwater

Remediation technologies are many and varied but can be categorised into **ex-situ** and **in-situ** methods. Ex-situ methods involve excavation of affected soils and subsequent treatment at the surface, In-situ methods seek to treat the contamination without removing the soils. The more traditional remediation approach (used almost exclusively on contaminated sites from the 1970s to the 1990s) consists primarily of soil excavation and disposal to landfill "dig and dump" and groundwater "pump and treat". In situ technologies include Solidification and Stabilization and have been used extensively in the USA.

2.1 Thermal desorption

Thermal desorption is a technology for soil remediation. During the process a desorber volatilizes the contaminants (e.g. oil, mercury or hydrocarbon) to separate them from especially soil or sludge. After that the contaminants can either be collected or destroyed in an offgas treatment system.

2.2 Excavation or dredging

Excavation processes can be as simple as hauling the contaminated soil to a regulated landfill, but can also involve aerating the excavated material in the case of volatile organic compounds (VOCs). Recent advancements in bioaugmentation and biostimulation of the excavated material have also proven to be able to remediate semi-volatile organic compounds (SVOCs) onsite. If the contamination affects a river or bay bottom, then dredging of bay mud or other silty clays containing contaminants may be conducted. Recently, ExSitu Chemical oxidation has also been utilized in the remediation of contaminated soil. This process involves the excavation of the contaminated area into large bermed areas where they are treated using chemical oxidation methods.

2.3 Surfactant enhanced aquifer remediation (SEAR)

Also known as Solubilization and recovery, the Surfactant Enhanced Aquifer Remediation process involves the injection of hydrocarbon mitigation agents or specialty surfactants into the subsurface to enhance desorption and recovery of bound up otherwise recalcitrant non aqueous phase liquid (NAPL).

In geologic formations that allow delivery of hydrocarbon mitigation agents or specialty surfactants, this approach provides a cost effective and permanent solution to sites that have been previously unsuccessful utilizing other remedial approaches. This technology is also successful when utilized as the initial step in a multi faceted remedial approach utilizing SEAR then In situ Oxidation, bioremediation enhancement or soil vapor extraction (SVE).

2.4 Pump and treat

Pump and treat involves pumping out contaminated groundwater with the use of a submersible or vacuum pump, and allowing the extracted groundwater to be purified by slowly proceeding through a series of vessels that contain materials designed to adsorb the contaminants from the groundwater. For petroleum-contaminated sites this material is usually activated carbon in granular form. Chemical reagents such as flocculants followed by sand filters may also be used to decrease the contamination of groundwater. Air stripping is a method that can be effective for volatile pollutants such as BTEX compounds found in gasoline.

For most biodegradable materials like BTEX, MTBE and most hydrocarbons, bioreactors can be used to clean the contaminated water to non-detectable levels. With fluidized bed bioreactors it is possible to achieve very low discharge concentrations which will meet or exceed discharge standards for most pollutants.

Depending on geology and soil type, pump and treat may be a good method to quickly reduce high concentrations of pollutants. It is more difficult to reach sufficiently low concentrations to satisfy remediation standards, due to the equilibrium of absorption (chemistry)/desorption processes in the soil. However, pump and treat is typically not the best form of remedation. It is expensive to treat the groundwater, and typically is a very slow process to cleanup a release with pump and treat. It is best suited to control the hydraulic gradient and keep a release from spreading further. Better options of in-situ treatment often include air sparge/soil vapor extraction (AS/SVE) or dual phase extraction/multiphase extraction(DPE/MPE). Other methods include trying to increase the dissolved oxygen content of the groundwater to support microbial degradation of the compound (especially petroleum) by direct injection of oxygen into the subsurface, or the direct injection of a slurry that slowly releases oxygen over time (typically magnesium peroxide or calium oxy-hydroxide).

2.5 Solidification and stabilization

Solidification/stabilization work has a reasonably good track record but also a set off serious deficiencies related to durability of solutions and potential longterm effects. In addition CO_2 emissions due to the use of cement are also becoming a major obstacle to its widespread use in solidification/stabilization projects.

Stabilization/solidification is a remediation/treatment technology that relies on the reaction between a binder and soil to stop/prevent or reduce the mobility of contaminants.

- **Stabilization** - involves the addition of reagents to a contaminated material (e.g. soil or sludge) to produce more chemically stable constituents; and
- **Solidification** - involves the addition of reagents to a contaminated material to impart physical/dimensional stability to contain contaminants in a solid product and reduce access by external agents (e.g. air, rainfall).

Conventional Stabilization/solidification is an established remediation technology for contaminated soils and treatment technology for hazardous wastes in many countries in the world. However, the uptake of Stabilization/solidification technologies has been relatively modest, and a number of barriers have been identified including:

- the relatively low cost and widespread use of disposal to landfill;

- the lack of authoritative technical guidance on Stabilization/solidification;
- uncertainty over the durability and rate of contaminant release from Stabilization/solidification -treated material;
- experiences of past poor practice in the application of cement stabilization processes used in waste disposal in the 1980s and 1990s (ENDS, 1992);
- residual liability associated with immobilized contaminants remaining on-site, rather than their removal or destruction.

2.6 In situ oxidation

New in situ oxidation technologies have become popular, for remediation of a wide range of soil and groundwater contaminants. Remediation by chemical oxidation involves the injection of strong oxidants such as hydrogen peroxide, ozone gas,potassium permanganate or persulfates.

Oxygen gas or ambient air can also be injected to promote growth of aerobic bacteria which accelerate natural attenuation of organic contaminants. One disadvantage of this approach is the possibility of decreasing anaerobic contaminant destructionnatural attenuation where existing conditions enhance anaerobic bacteria which normally live in the soil prefer a reducing environment. In general though, aerobic activity is much faster than anaerobic and overall destruction rates are typically greater when aerobic activity can be successfully promoted.

The injection of gases into the groundwater may also cause contamination to spread faster than normal depending on the site's hydrogeology. In these cases, injections downgradient of groundwater flow may provide adequate microbial destruction of contaminants prior to exposure to surface waters or drinking water supply wells.

Migration of metal contaminants must also be considered whenever modifying subsurface oxidation-reduction potential. Certain metals are more soluble in oxidizing environments while others are more mobile in reducing environments.

2.7 Soil vapor extraction

Soil vapor extraction (SVE) is an effective remediation technology for soil. “Multi Phase Extraction” (MPE) is also an effective remediation technology when soil and groundwater are to be remediated coincidentally. SVE and MPE utilize different technologies to treat the off-gas volatile organic compounds (VOCs) generated after vacuum removal of air and vapors (and VOCs) from the subsurface and include granular activated carbon (most commonly used historically), thermal and/or catalytic oxidation and vapor condensation. Generally, carbon is used for low (<500ppmV) VOC concentration vapor streams, oxidation is used for moderate (up to 4,000 ppmV) VOC concentration streams, and vapor condensation is used for high (>4,000 ppmV) VOC concentration vapor streams. Below is a brief summary of each technology.

1. Granular activated carbon (GAC) is used as a filter for air or water. Commonly used to filter tap water in household sinks. GAC is a highly porous adsorbent material, produced by heating organic matter, such as coal, wood and coconut shell, in the absence of air, which is then crushed into granules. Activated carbon is positively charged and therefore able to remove negative ions from the water such as organic ions, ozone, chlorine, fluorides and dissolved organic solutes by adsorption onto the activated carbon. The activated carbon must be replaced periodically as it may become saturated and unable to adsorb (i.e. reduced absorption efficiency with loading). Activated carbon is not effective in removing heavy metals.

2. Thermal oxidation (or incineration) can also be an effective remediation technology. This approach is somewhat controversial because of the risks of dioxins released in the atmosphere through the exhaust gases or effluent off-gas. Controlled, high temperature incineration with filtering of exhaust gases however should not pose any risks. Two different technologies can be employed to oxidize the contaminants of an extracted vapor stream. The selection of either thermal or catalytic depends on the type and concentration in parts per million by volume of constituent in the vapor stream. Thermal oxidation is more useful for higher concentration (~4,000 ppmV) influent vapor streams (which require less natural gas usage) than catalytic oxidation at ~2,000 ppmV.

- Thermal oxidation which uses a system that acts as a furnace and maintains temperatures ranging from 732 to 800 °C.

- Catalytic oxidation which uses a catalyst on a support to facilitate a lower temperature oxidation. This system usually maintains temperatures ranging from 300 to 400 °C.

3. Vapor condensation is the most effective off-gas treatment technology for high (>4,000 ppmV) VOC concentration vapor streams. The process involves cryogenically cooling the vapor stream to below 40 degrees Celsius such that the VOCs condensate out of the vapor stream and into liquid form where it is collected in steel containers. The liquid form of the VOCs is referred to as dense non-aqueous phase liquids (DNAPL) when the source of the liquid consists predominantly of solvents or light non-aqueous phase liquids (LNAPL) when the source of the liquid consists predominantly of petroleum or fuel products. This recovered chemical can then be reused or recycled in a more environmentally sustainable or green manner than the alternatives described above. This technology is also known as cryogenic cooling and compression (C3-Technology).

2.8 Other technologies

The treatment of environmental problems through biological means is known as bioremediation and the specific use of plants for example by using phytoremediation. Bioremediation is sometimes used in conjunction with a pump and treat system. In bioremediation, either naturally occurring or specially bred bacteria are used to consume contaminants from extracted groundwater. This is sometimes referred to as a bio-gac system. Many times the groundwater is recycled to allow for continuously flowing water and enhanced bacteria population growth. Occasionally the bacteria can build up to such a point that they can affect filtration and pumping. The vessel should then be partially drained. Care must be taken to ensure that a sharp change in the groundwater chemistry does not kill the bacteria (such as a sudden change in pH).

Dual-phase extraction utilizes a soil vapor extraction system that produces a high vacuum resulting in the extraction of both contaminated vapors as well as a limited amount of contaminated groundwater. This method is somewhat inefficient due to large amount of energy required by pulling water by vacuum compared to pushing water with a submersible pump.

Mycoremediation is a form of bioremediation, the process of using fungi to return an environment (usually soil) contaminated by pollutants to a less contaminated state.

In an experiment conducted in conjunction with Batelle, a major contributor in the bioremediation industry, a plot of soil contaminated with diesel oil was inoculated with mycelia of oyster mushrooms; traditional bioremediation techniques (bacteria) were used on control plots. After four weeks, more than 95% of many of the PAH (polycyclic aromatic hydrocarbons) had been reduced to non-toxic components in the mycelial-inoculated plots. It appears that the natural microbial community participates with the fungi to break down contaminants into carbon dioxide and water. Wood-degrading fungi are particularly effective in breaking down aromatic pollutants (toxic components of petroleum), as well as chlorinated compounds (certain persistent pesticides; Battelle, 2000). Hair mats inoculated with oyster mushrooms were successfully employed in the clean-up of the San Francisco Bay area oil spill in 2007.

The key to mycoremediation is determining the right fungal species to target a specific pollutant. Certain strains have also been reported to successfully degrade the nerve gases VX and sarin. Mycofiltration is a very similar process, using mycelial mats to filter toxic waste and microorganisms from polluted water.

3 Biological degradation

As much as the diversity in sources and chemical complexities in organic pollutants exists, there is probably more diversity in microbial members and their capabilities to synthesize or degrade organic compounds. Microbial populations even contribute to naturally-occurring hydrocarbons by diagenesis of bacteriohopanetetrol (a membrane constituent) into the formation of hopanoic acids and hydrocarbons such as hopane (Stout et al., 2001). The microbial diversity is larger than what is known from the cultured members (Curtis et al., 2002). However, the metabolic diversity of culturable microorganisms for degrading organic pollutants may be insufficient to protect the earth from the anthropogenic pollution. This is largely due to recalcitrant chemicals with substituent or structural elements, which seldom occur in nature (Pieper and Reineke, 2000). But, Singer et al. (2004) were of the opinion that the naturally-occurring tritrophic trinity of microbe–plant–insect interactions has capabilities to produce hundreds of thousands of different chemicals to attract, defend, antagonize, monitor and misdirect one another among these members and only negligible numbers are truly novel chemicals of anthropogenic origin. Hence, there is a fortuitous evolution of xenobiotic-degrading enzymes from the interactions of microbe–plant–insect.

The potential to degrade organic pollutants varies among microbial groups or different guilds (group of species that exploit the same class of environmental resources in a similar way) and is dose-dependent. For example, mycobacteria are excellent candidates for remediating aged PAH-polluted sites as these organisms have lipophilic surfaces, suitable for uptake of bound pollutants from soil particles and have catabolic efficiency towards PAHs up to five benzene rings (Bogan et al., 2003). Higher doses of PAHs are phytotoxic to algae including microalgae. The inhibitory or toxic components of the pollutant mixture can attenuate the potential of microbial degradation and are important stressors. Organic compounds such as toluene are toxic to microorganisms because they disrupt cell membranes. Providentially, several bacteria develop resistance to solvents by the ***cis*** to ***trans*** isomerization of fatty acids, increased synthesis of phospholipids, low cell-surface hydrophobicity (modification of the lipopolysaccharide or porines of the outer membrane), and the presence of solvent efflux pump. In the soils polluted by aromatic hydrocarbons, the solvent-tolerant microorganisms are the first to colonize and become predominant in the removal of pollutants (Huertas et al., 1998). Either bioaugmentation with the solvent-tolerant bacteria or modifying these bacteria with an appropriate catabolic potential will provide advantages in bioremediation programs.

The microbial populations of soil or aquatic environments are composed of diverse, synergistic or antagonistic communities rather than a single strain. In the natural environments, biodegradation involves transferring the substrates and products within a well coordinated microbial community, a process referred to as metabolic cooperation (Abraham et al., 2002). It still remains very challenging to introduce all the genes required for degradation for many organic pollutants or stable maintenance of even a single gene or a desired trait such as enhanced degradative capacity in a single organism. Hence, the microbial consortia of ecologically relevant candidate taxa which are known to degrade the chemical pollutants and respond to different environmental stimuli are desired, rather than the single isolate for augmentation (Supaphol et al., 2006).

The reductionist approach to studying biodegradation processes has been very useful so far for understanding individual genes, enzymes and organisms, but the systems biology approach is necessary to examine the complex web of metabolic and regulatory interactions even within a single organism (Pazos et al., 2003 and Trigo et al., 2009). Pazos et al. (2003) considered the biodegradation process as a single interconnecting network (metabolic cooperation), with metabolic activities and substrates and intermediate compounds flowing freely in the environment and less boundaries existing between bacterial species. The 'network theory,' thus forms a basis for studying the functional properties and mechanisms involved in the organization of biological systems and predicting their responses to environmental (both internal and external) variations (Feist and Palsson, 2008).

Formalization and categorization of many biodegradation reactions and pathways have been done in the University of Minnesota Biocatalysis/Biodegradation Database (UM-BBD) (Ellis et al., 2006). With information on about 900 compounds, 600 enzymes, 1000 reactions and 350 microbial entries, the UM-BBD is useful for applying the system biology approaches. The most likely metabolic pathway for any given compound is predictable using the 'reaction rules' for particular functional groups (Ellis et al., 2008). Pazos et al. (2005) developed a database, 'Metarouter', based on the information available at the UM-BBD. Using the Metarouter, Gomez et al. (2007) showed the existence of a correlation between the frequency of 149 chemical triads (chemotypes) common in organo-chemical compounds and the global capacity of microorganisms to metabolize them. These authors developed a predictive tool (http://www.pdg.cnb.uam.es/BDPSERVER) which can provide the biodegradative outcome of the compounds as biodegradable or recalcitrant, depending on the type of environmental fate defined. Trigo et al. (2009) suggested that (i) the central metabolism of the global biodegradation networks involves transferases, isomerases, hydrolases and ligases, (ii) linear pathways converging on particular intermediates form a funnel topology, (iii) the novel reactions exist in the exterior part of the network, and (iv) the possible pathway between compounds and the central metabolism can be arrived at by considering all the required enzymes in a given organism and intermediate compounds.

Biodegradation in the natural environment is beyond the 'complete system' of a single cell, where the 'system' is extremely complex involving multiple biotic and abiotic components. Nevertheless, there exists the coordination of microbial communities to mediate and transfer substrates and products between species and communities (Abraham et al., 2002). The application of molecular site assessment (Fleming et al., 1998 and Sayler et al., 1995) and molecular ecological techniques for community profiling (Malik et al., 2008), soil metagenomics using isotope distribution analysis (Villas-Boas and Bruheim, 2007), and functional genomics and proteomics (Zhao and Poh, 2008) can help in identifying the partners and the patterns of responses to external stimuli within the network and the 'system complexities' of contaminated sites. Stable isotope probing (SIP) analyses, either DNA-SIP (Winderl et al., 2010) or RNA-SIP (Bombach et al., 2010), provide opportunities to link microbial diversity with function and identify those culturable as well as yet-to-be cultured organisms which are involved in biodegradation in the field (Cupples, 2011). Likewise, the high-throughput approaches such as DNA microarrays, metagenomics, metatranscriptomics, metaproteomics, metabolomics, and whole cell-based biosensors are useful to characterize the contaminated sites, identify new degradative activities and monitor bioremediation efficiency.

4 Bioremediation with bacteria, fungus, enzymes

4.1 Basics

Bioremediation, which is defined as a process that uses microorganisms, green plants or their enzymes to treat the polluted sites for regaining their original condition (Glazer and Nikaido, 1995), has considerable strength and certain limitations. Remediation, whether by biological, chemical or a combination of both means, is the only option as the problem of pollution has to be solved without transferring to the future. As the knowledge demand and complexities vary for different bioremediation treatments, a better understanding of the premises together with the limitations of bioremediation aids in maximizing the benefits and minimizing the cost of treatments.

The process of bioremediation depends on the metabolic potential of microorganisms to detoxify or transform the pollutant molecule, which is dependent on both accessibility and bioavailability (Antizar-Ladislao, 2010). There is a considerable debate in the literature on "what constitutes the bioavailable fraction" and the methods of its measurements (Alexander, 2000 and Vasseur et al., 2008). Following entry into the soil environment, pollutants rapidly bind to the mineral and organic matter (solid phases) via a combination of physical and chemical processes. Sorption, complexation and precipitation constitute the pollutant–soil interaction. The ability of soils to release (desorb) pollutants determines its susceptibility to microbial degradation, thereby influencing effectiveness of the bioremediation process. In soil aggregates which are the smallest 'composite units' in the heterogeneous soil environment, bioavailability is limited by transport of the pollutant molecule to a microbial cell, i.e., diffusion of pollutant out of a soil aggregate to the cell attached to the external surface of the aggregate.

Sorption which influences the bioavailability of a contaminant is a critical factor, yet a poorly understood process in bioremediation. There are two schools of thought concerning bioavailability and the consequent biodegradation of organic contaminants (Singh et al., 2008): (i) the pre-requisite release of contaminant from sorbed phase to aqueous phase for its degradation by microorganisms (Harms and Zehnder, 1994 and Shelton and Doherty, 1997), and (ii) biodegradation of the contaminant in the sorbed phase, without being desorbed, by the enzymes (Singh et al., 2003). The degradation of sorbed contaminants can presumably occur via microbially-mediated desorption of contaminants through production of biosurfactants and the development of a steep gradient between solid phase and interfacial contaminant (Tang et al., 1998). Thus, these reports suggest that bioavailability is even species specific (i.e., the ability of certain species to desorb the contaminant and then degrade). The organic contaminants can also be degraded without prior desorption. Singh et al. (2003) demonstrated that a soil bacterium, ***Brevibacterium*** sp. degraded the pesticide fenamiphos which was intercalated into the cationic-surfactant modified montmorillonite clay (CTMA–Mt–fenamiphos complex). The interlayer space is otherwise inaccessible to the bacterium due to its size of several orders lower than that of the bacteria. The scanning electron microscope analysis showed the surface attachment of bacteria to the surface of the CTMA–Mt–fenamiphos complex, suggesting the involvement of extracellular enzyme in the degradation of fenamiphos, without its prior desorption. The degradation of sorbed contaminants depends on the enrichment and isolation procedures used for obtaining the culturable bacteria. As against the conventional approach of providing the contaminant as a sole carbon source in aqueous medium, the provision of phenanthrene sorbed on a polyacrylic porous resin to the bacterial cultures led to faster degradation of phenanthrene than those isolated by the conventional technique (Grosser et al., 2000 and Tang et al., 1998).

Aqueous solubility, volatility or reactivity of organic pollutants varies greatly, and all of them may influence their bioavailability in water and soils. On a mass basis, no relationship exists between the chemical pollutant in soil and its biological effect. The dissolved form of contaminants in pore water is considered to be bioavailable, compared to the bound chemical which does not exert direct biological effects. This has led to the 'pore water hypothesis.' The equilibrium partitioning theory is applied to estimate the dissolved fraction of pollutant in pore water and to remove the ***soil to soil*** differences in toxicological effects. The basic assumption of equilibrium partitioning theory is that the partitioning of an ionic chemical between the mineral and organic matter in soil or sediment and the pore water is at equilibrium, and in each phase the chemical potential which controls its biological activity is the same. The performance of chemical extraction data of nonionic organic chemicals can be improved by organic matter normalization in order to predict the occurrence of toxicity effects.

For highly hydrophobic chemical pollutants which have higher octanol–water partition coefficient (K_{ow}) with log K_{ow} values more than 4, the measured concentration in the pore water is the sum of the free chemical and the fraction sorbed to dissolved organic matter (DOM). To account for the sorbed fraction to DOM, the separation methods for DOM are required (Landrum et al., 1984). The soil–chemical contact time determines the usefulness of pore water hypothesis in measuring bioavailability and predicting the biological effects or the fraction which can be degraded, but not immediately after contamination. There are also variations in bioavailability due to the nature of chemical pollutants, soil types, and other factors such as water content and temperature. Toxicity testing of a pollutant to microorganisms (Ronday et al., 1997) or the use of extracts such as the mild hydroxypropyl-β-cyclodextrin for PAHs (Ling et al., 2010) or the matrix solid-phase microextraction for DDTs (1,1,1-trichloro-2,2-bis(***p***-chlorophenyl) ethane and its metabolites) (Fang et al., 2010) can provide direct measures of bioavailability. Cornelissen et al. (1998) demonstrated that microbial factors, not bioavailability, were responsible for the persistence of rapidly desorbing fractions of the nondegraded PAHs, and these fractions were found to be substantial (up to 55%) and remained unchanged during remediation. For the purpose of bioremediation and regulatory measures, the bioavailability in the initial rapid phase and the ensuing slow phase in the biphasic degradation profile of an organic pollutant is to be monitored.

The sequestration of pollutants over time may occur due to the contact and interaction of soil with pollutant molecules. Factors such as organic matter, cation exchange capacity, micropore volume, soil texture and surface area affect the pollutant sequestration (Chung and Alexander, 2002). Sequestration and reduced bioavailability of phenanthrene were reported for a Gram-negative bacterial isolate (strain PS5-2) when the hydrophobic compound entered into nanopores having hydrophobic surfaces (Nam and Alexander, 1998).Sharer et al. (2003) observed that aging caused an increase in sorption for some organic compounds (e.g., 2,4-dichlorophenoxyacetic acid) but not for others (chlorobenzene, ethylene dibromide) on a common soil type. Even a weakly sorbed and easily degraded carbamate insecticide, carbaryl, can be effectively sequestrated in soil with aging, thereby rendering it partly inaccessible to microorganisms and affecting the bioavailability (Ahmad et al., 2004). Hence, the generalizations about the effects of aging on the sorption–desorption behavior of different organic chemicals are difficult to achieve. Some pertinent issues that need to be considered include: (a) bioavailability and toxicity of parent molecules and their residues in soils, (b) standardized protocols for different pollutants and their use across the sites, (c) assessment on remobilization of pollutants during the post-remediation period, and (d) determination of environmentally acceptable pollutant end-points in the bioremediated soils. The 'pollutant (or contaminant) sequestration' due to the prolonged contact between soil particles and chemical molecules, however, poses less risk and threat to the environmental health. In general, difficulties with analytical measurements for determining low levels of new organic pollutants in soils, the absence of base-line values related to their compositional, geographical and distribution patterns, and the complexities in their toxicological interactions (Mas et al., 2010) make the bioavailability measurements of organic pollutants exigent.

Application of surfactants to polluted soils has been used as one of the treatment strategies for increasing the mass transfer of hydrophobic organic contaminants. The surfactants are amphiphilic molecules that contain hydrophilic and hydrophobic moieties; hydrophilic groups can be anionic, cationic, zwitter ionic, and nonionic. The synthetic surfactants contain sulfate, sulfonate or carboxylate group (anionic); quaternary ammonium group (cationic); polyoxyethylene, sucrose, or polypeptide (nonionic) and the hydrophobic parts of paraffins, olefins, alkylbenzenes, alkylphenols, or alcohols. The common chemical surfactants such as Triton X-100, Tween 80 and sodium dodecyl sulphate are petroleum-derived products. The zwitter ionic surfactants (e.g., ***N***-dodecyl betaine) which contain both anionic and cationic groups have low critical micelle concentration (CMC) values, more surface active, and high solubilization capacity. Increased desorption rates of sorbed pollutants from soils by the application of surfactants make the pollutants available for remediation (Fu and Alexander, 1995). Solubilization of hydrophobic contaminants is attributed to the incorporation of the molecule into the hydrophobic core of micelles in solution (Guha and Jaffe, 1996). The salient mechanisms which are involved in the surfactant-amended remediation are: (i) lowering of interfacial tension, (ii) surfactant solubilization of hydrophobic organic compounds, and (iii) the phase transfer of organic compounds from soil-sorbed to pseudo-aqueous phase (Laha et al., 2009).

Surfactants enhance mobilization and biodegradation of PAHs in soils (Tiehm et al., 1997). Enhanced rates of degradation of naphthalene and phenanthrene in the presence of some nonionic surfactants at applications below their CMC were observed by Aronstein et al. (1991). Similarly, significant solubility enhancements of

DDT in Triton and Brij 35 surfactants were noticed by Kile and Chiou (1989) below their CMC. Factors such as cost, effectiveness at concentrations lower than 3%, low toxicity to humans, animals and plants, low adsorption to soil, low soil dispersion, and low surface tension determine the selection of surfactants for field application (Mulligan et al., 2001). Toxicities of surfactants to soil biota can prevent the biodegradation of pollutants and disturb the balanced ecological functions.

The food-grade surfactants (T-MAZ 28, T-MAZ 10, and T-MAZ 60), the plant-based surfactants (e.g., fruit pericarp from ***Sapindus mukurossi***) or the natural surfactants such as humic acids may be preferred to the synthetic surfactants due to high biodegradability, low toxicity, and higher public acceptance. Microorganisms also produce surfactants (surface-active amphiphilic metabolites such as glycolipids, phospholipids, lipopeptides, lipoproteins, and lipopolysaccharides). These low- and high-molecular weight biosurfactants find their uses in food processing, cosmetic and pharmaceutical industries, in addition to bioremediation efforts (Christofi and Ivshina, 2002). The classes of biosurfactant and microbial species which can produce them are numerous, leading to continuous search for the novel biosurfactants (Satpute et al., 2010). However, the ***in situ*** application of surfactants to enhance bioavailability of persistent organic pollutants requires careful planning and selection based on the prior information about the fate and behavior of the surfactant and the target pollutant. Caution is required to prevent groundwater contamination via leaching and consequent toxicity to microorganisms. Hence, a good strategy will be to select bacteria that are capable of not only catabolizing the target contaminant but also producing surfactant. More knowledge on the mechanisms of pollutant–surfactant interactions with regard to diffusion, in and out of the micelles, and modeling of pollutant's transport at the field site can help to design efficient remediation strategy.

4.2 In situ and ex situ bioremediation

Bioremediation approaches are generally classified as ***in situ*** or ***ex situ***. ***In situ*** bioremediation involves treating the polluted material at the site while ***ex situ*** involves the removal of the polluted material to be treated elsewhere (Aggarwal et al., 1990). ***In situ*** bioremediation can be described as the process whereby organic pollutants are biologically degraded under natural conditions to either carbon dioxide and water or an attenuated transformation product. It is a low-cost, low maintenance, environment-friendly and sustainable approach for the cleanup of polluted sites. With the need for excavation of the contaminated samples for treatment, the cost of ***ex situ*** bioremediation approaches can be high, relative to ***in situ*** methods. In addition, the rate of biodegradation and the consistency of the process outcome differ between the ***in situ***- and ***ex situ*** bioremediation methods. While the methods of both ***in situ*** and ***ex situ*** remediation depend essentially on microbial metabolism, the ***in situ*** bioremediation methods are preferred to those of ***ex situ*** for ecological restoration of contaminated soil and water environments (Jorgensen, 2007). Three different types of ***in situ*** bioremediation process are (i) bioattenuation which depends on the natural process of degradation, (ii) biostimulation where intentional stimulation of degradation of chemicals is achieved by addition of water, nutrient, electron donors or acceptors, and (iii) bioaugmentation where the microbial members with proven capabilities of degrading or transforming the chemical pollutants are added (Madsen, 1991). The suitability of a particular bioremediation technology is determined by several factors, such as site conditions, indigenous population of microorganism, and the type, quantity and toxicity of pollutant chemical species present.

4.2.1 Bioattenuation

During bioattenuation (natural attenuation), the pollutants are transformed to less harmful forms or immobilized. Such transformation and immobilization processes are largely due to biodegradation by microorganisms (Smets and Pritchard, 2003), and to some extent by the reactions with naturally-occurring chemicals and sorption on the geologic media. The natural attenuation processes are contaminant-specific, accepted as methods for treating fuel components (e.g., BTEX) (Atteia and Guillot, 2007), but not for many other classes. The time required for natural attenuation varies considerably with site conditions. Many polluted sites may not require an aggressive approach to remediation, and bioattenuation is efficient and cost-effective (Davis et al., 1994 and Mulligan and Yong, 2004). In fact, a variety of bioremediation techniques have been successfully employed at over 400 cleanup sites throughout the USA, at costs which are approximately 80–90% lower than other cleanup technologies, based on the physical and chemical principles. With minimal site disturbance, the post-cleanup costs are also substantially reduced. Consequently, the global demand for bioremediation along with phytoremediation technologies is valued to be about US $1.5 billion per annum (Singh et al., 2009). Industrial and environmental biotechnologies also prefer newer paths, resulting in processes with 'clean technologies', with maximum production and fewer residues. Bioattenuation alone becomes inadequate and protracted in many cases since many soils are oligotrophic in nature or lack appropriate microorganisms.

4.2.2 Biostimulation

The acceleration of microbial turnover of chemical pollutants generally depends on the supply of carbon, nutrients such as N and P, temperature, available oxygen, soil pH, redox potential, and the type and concentration of organic pollutant itself (Carberry and Wik, 2001). To stimulate microbial degradation, nutrients in the form of fertilizers (water soluble (e.g., KNO_3, $NaNO_3$, NH_3NO_3, K_2HPO_4 and $MgNH_4PO_4$), slow release (e.g., customblen, IBDU, max-bac), and oleophilic (e.g., Inipol EAP22, F1, MM80, S200)) are added (Nikolopoulou and Kalogerakis, 2008). As a thumb rule for oil spill remediation, around 1–5% N by weight of oil with a ratio of N:P between 5 and 10:1 is applied (Swannell et al., 1996). These additions may be insufficient or inaccurate for polluted sites with different types of pollutants. Formulation of nutrient-treatment strategies and maintenance of control on the degradation rates and the outcomes of degradation need to be tailored to specific site/pollutant combinations. Limitations of nutrients such as nitrogen and phosphorus on microbial decomposition of organic matter and the possible ecological implications of these effects for carbon flow through natural ecosystems are well known (Sterner and Elser, 2002). Wolicka et al. (2009)optimized the C:N:P ratio (at the level of 100:9:2, 100:10:1 or 250:10:3) before commencing ***in situ*** remediation of BTEX.

The 'ecological stoichiometry' is concerned with the supplies of nutrients, and their elemental stoichiometry relative to the nutritional demands of the cell's innate physiology. It also exemplifies the effects of resource (nutrient) supply rates and supply ratios on the structure and function of microbial communities (Smith, 2002). Smith et al. (1998) applied the resource-ratio theory to hydrocarbon degradation and demonstrated that the changes in nitrogen and phosphorus supply ratios not only altered the biodegradation rates of hydrocarbons (hexadecane and phenanthrene) but also the microbial community composition significantly. In addition, the changes in absolute nutrient supply levels, at constant supply ratio, were found to alter total hydrocarbon degrader biomass, with altered rates of hydrocarbon degradation. The 'resource-ratio approach' to gain information on the ecophysiological status of pollutant-degrading microorganisms has many practical implications. Basically, it provides the theoretical framework for optimizing nutrient formulation and application in biostimulation approaches.

4.2.3 Bioaugmentation

Often, the biological response lags behind, up to weeks or months, in the polluted sites with no exposure history. The 'soil activation,' a concept which is based on the cultivation of biomass from a fraction of a contaminated soil and the subsequent use as an inoculum for bioaugmentation for the same soil was attempted by Otte et al. (1994) for degradation of PCP and PAHs. The soils with microbiota, adapted by prior exposure to degradation of organic pollutants such as hydrocarbons can be a source of microorganisms for remediating soils freshly contaminated with hydrocarbons. Priming with 2% bioremediated soil was found to increase biodegradation of PAH constituents of a fuel oil-treated soil (Lamberts et al., 2008). Similar priming effect of exhaustively bioremediated soils for hydrocarbon degradation was observed by Greenwood et al. (2009). Exposure history and adaptive status of microbial degraders thus determine the lag period of degradation. In addition, ascertaining the history of exposure of chemical pollutants in the contaminated sites has even become significant in the environmental forensics such as the 1989 Exxon Valdez oil spill case (Peters et al., 2005) and for ecological engineering such as the 2010 Gulf of Mexico oil spill case (Mitsch, 2010).

Pre-adaptation of catabolic bacteria to the target environment, prior to inoculation, improves survival, persistence and degradative activities, leading to enhanced remediation of the polluted soil (Megharaj et al., 1997). ***Sphingomonas*** sp. RW1 which contained a mini transposon Tn-5 ***lacZ*** was pre-adapted to soil by growing in the soil extract medium. The pre-adapted bacterium exhibited better survival and efficient degradation of dibenzo-***p***-dioxin and dibenzofuran in the polluted soil, compared to the unadapted bacterium, grown only in the nutrient-rich medium. Sudden exposure to stresses in soil (oligotrophic conditions that generally exist in soils, starvation or susceptibility/resistance, etc.) determines the physiological response of bacteria and their subsequent survival and activities.

Pre-exposure and subsequent re-exposure of a chemical pollutant enhances the metabolic potential of microorganisms (Reddy and Sethunathan, 1983). The phenomenon of retaining specific metabolic capacity after pre-exposure over long periods of time is referred to as 'soil memory.' The soil memory makes a contribution to the subsequent natural attenuation. Now, in a typical bioaugmentation approach, microorganisms are amended to a polluted site to hasten detoxification and/or degradation. There are many reports on bioaugmentation for treatment of soils containing organic pollutants (Brunner et al., 1985). Gilbert and Crowley (1998) found that the repeated application of carvone-induced bacteria enhanced biodegradation of PCBs in soil. To improve efficiency of bioaugmentation, microorganisms of different physiological groups and of different divisions can also be brought together. Bender and Phillips (2004) suggested the use of microbial mats which occur in nature as stratified communities of cyanobacteria and bacteria to remediate organic contaminants by degrading and completely mineralizing the contaminants. Wolicka et al. (2009)applied aerobic microbial communities, selected from those adapted to utilize one type of BTEX compound, for bioremediation of soil contaminated with BTEX.

A successful strategy for in situ bioremediation can be the combination, in a single bacterial strain or in a syntrophic bacterial consortium, of different degrading abilities with genetic traits that provide selective advantages in a given environment (Diaz, 2004). The present strain selection procedures dwell on isolating 'superbugs' with high resilience to environmental stresses, those harboring catabolically superior enzymes, and those species that are not human pathogens (Singer et al., 2005). Most laboratory strains which are capable of degrading organic pollutants constitute a fraction of culturable microorganisms, making only small contributions to bioaugmentation (Watanabe, 2001). Paul et al. (2005) also pointed out that only a fraction of total microbial diversity has been harnessed so far while the genetic resource for degradation of recalcitrant and xenobiotic pollutants is vast.

Bioaugmentation efforts are met with failures more often due to lesser efficiency, competitiveness and adaptability, relative to the indigenous members of natural communities. For example, the well known bacteria capable of degrading PCBs in laboratory culture media survived poorly in natural soils, and when these strains were inoculated to remediate PCB-contaminated soils, the resultant was the failure of bioaugmentation (Blasco et al., 1995). Further investigations revealed that formation of an antibiotic compound, protoanemonin, from 4-chlorocatechol via the classical 3-oxoadipate pathway by the native microorganisms was the reason for poor survival of the introduced specialist PCB-degrading strains. Indeed, bioaugmentation itself is undesirable in all the environmentally sensitive locations, especially those protected from the introduction of exotic flora or fauna. Scott et al. (2010) proposed a new strategy of using a free enzyme-based product to remediate water bodies contaminated with atrazine. The ecological or environmental issues associated with degrading organisms can be circumvented by this strategy. The soils do have exoenzymes (cell-free enzymes) which include proteases, and the presence of proteases along with other inhibitors may limit the longevity of free enzymes applied for bioremediation. The cell-free approach can only be used for viable and efficient enzymes that are not dependent on diffusible co-factors such as NAD (particularly hydrolases), and cannot be applied in cases where the enzyme activity (e.g., most oxygenases) is lost when the cells are broken (Scott et al., 2008). Orica Watercare (Australia) has commercialized for the first time a free-enzyme for phosphotriester insecticides under the trade name LandGuardTM which was proven to be successful and cost effective. Nevertheless, the technical feasibility of such strategy needs careful evaluation for many contaminants or their mixtures. Immobilizing enzymes on suitable carriers will make them more stable and resistant to changes in pH, temperature and substrate concentrations (Gainfreda and Rao, 2004 and Kandelbauer et al., 2004). Other limitations for enzymes include: (a) expensive production costs for pure enzymes, (b) reduced activity due to sorption in soils requiring repeated doses, and (c) the issues with delivery of enzymes, immobilized enzymes in particular, to come in contact with the pollutant in the contaminated site. Selection of suitable carrier materials for immobilizing enzymes will not only help to increase their longevity but also allow their re-use thus making them more cost-effective. Further research into cheap nutrient sources for growing microorganisms may lower production costs of pure enzymes. Also, more research is required into the mechanisms of delivery of enzymes for their in situ application.

Most of the biosurfactants are anionic or nonionic; the structure is a characteristic of the microorganism producing the surfactant under the specific growth conditions (Mulligan and Gibbs, 1993 and Zhang and Miller, 1995). Relative to a synthetic surfactant (Tween-80), the biosurfactant (rhamnolipid) was found to enhance the solubility and the subsequent degradation of phenanthrene by Sphingomonas sp. (Pei et al., 2010). The biosurfactants can be toxic or even utilized preferentially by the pollutant-degrading microorganisms. But, the application of biosurfactant-producing and pollutant-degrading microorganisms offers dual advantages of a continuous supply of biodegradable surfactant and the ability to degrade pollutant(s) (Moran et al., 2000 and Rahman et al., 2002). In a recent report, Hua et al. (2010) demonstrated that a salt-tolerant Enterobacter cloacae mutant could be used as an agent for bioaugmentation of petroleum- and salt-contaminated soil due to increased K+ accumulation inside and exopolysaccharide level outside the cell membrane.

Microorganisms respond differently to various kinds of stresses and gain fitness in the polluted environment. This process can be accelerated by applying genetic engineering techniques. The recombinant DNA and other molecular biological techniques have enabled (i) amplification, disruption, and/or modification of the targeted genes that encode the enzymes in the metabolic pathways, (ii) minimization of pathway bottlenecks, (iii) enhancement of redox and energy generation, and (iv) recruiting heterologous genes to give new characteristics (Liu et al., 2006, Shimizu, 2002 and Timmis and Piper, 1999). Various genetic approaches have been developed and used to optimize the enzymes, metabolic pathways and organisms relevant for biodegradation (Pieper and Reineke, 2000). New information on the metabolic routes and bottlenecks of degradation is still accumulating, requiring the need to reinforce the available molecular toolbox (Stegmann, 2001). Nevertheless, the introduced genes or enzymes, even in a single modified organism, need to be integrated within the regulatory and metabolic network for proper expression (Cases and Lorenzo, 2005).

There are some drawbacks with the field release of genetically engineered microorganisms (GEMs), which include the decreased levels of fitness and the extra energy demands imposed by the presence of foreign genetic material in the cells (Saylor and Ripp, 2000 and Singh et al., 2011). More importantly, there remains a great risk of mobile genetic elements entering the environment and being acquired by undesirable organisms. The biotechnological innovations for making GEMs are numerous. According to Pandey et al. (2005), the advances such as the programmed cell death based on the principle of killer–anti-killer gene(s) after detoxification can help to develop 'suicidal genetically engineered microorganisms' (S-GEMs) that can lead to safe and efficient bioremediation. Few GEMs have been used for field application because of strict regulations for the release of GEMs into the environment (Ezezika and Singer, 2010). The only GEM approved for field testing in the USA for bioremediation was Pseudomonas fluorescens HK44, possessing a naphthalene catabolic plasmid (pUTK21), mutagenized by transposon insertion of lux genes (Ripp et al., 2000). The transition of genetically engineered microorganisms from the laboratory to the field environments is hampered due to the lack of information on the population dynamics of introduced genetically engineered microorganisms in the field and poor physiological control of catabolic gene expression in the engineered organisms under nutrient and other stresses (Cases and Lorenzo, 2005). The bioengineering and environmental release of those engineered microorganisms has to overcome several obstacles which include inconsistencies in risk assessment procedures and public health concerns before their effective application in the field. Selecting an indigenous bacterium able to grow rapidly and withstand the local stressful conditions for genetic engineering to enhance the biodegradation capabilities will be more advantageous over other bacterial strains. We hope, in 5 to 10 years from now, research into the field release of GEMs will help in designing them for alleviation or prevention of any perceived risks and eventually gaining public and regulatory acceptance in bioremediation of contaminated sites.

4.3 Bioremediation technologies

Bioremediation technologies based on the principles of biostimulation and bioaugmentation include bioventing, land farming, bioreactor, and composting. From these technologies which are at different stages of development in terms of experimentation and acceptance, the choice of technology option can be made considering many factors which include the class of organic contaminants and the cost of operation. Sebate et al. (2004) proposed a protocol for biotreatability assays in two phases, for the successful application of bioremediation technology. In the first phase, the type and metabolic activity of indigenous microorganisms at the polluted site and the presence of possible inhibitors are to be assayed to know whether bioremediation itself is appropriate. In the second phase, the influences of nutrients, surfactant, and specialized inocula amendment are to be evaluated in microcosms to identify the appropriate treatment for the polluted site. Recently, Bento et al. (2005) reiterated the need for a detailed site-specific characterization studies since the soil properties and the indigenous soil microbial population affect the degree of biodegradation. These conclusions were drawn from a comparative study on natural attenuation, biostimulation and bioaugmentation on degradation of total petroleum hydrocarbons (TPHs) in contaminated soils collected from Long Beach, California, USA and Hong Kong, China. Improvements in reliability, cost efficiency and speed of remediation can be achieved by the use of various methods ranging from minimal intervention (bioattenuation), through in situ introduction of nutrients and/or bacterial inocula, improvements of physicochemical conditions or development of novel methods (Romantschuk et al., 2000).

The fate of pollutants is largely influenced by the competing processes of degradation and sorption which refers to both adsorption, occurring on surfaces (e.g., between a charged compound and clay) and absorption, i.e., the sorption beyond the surface into a separate portion defined by the surface (e.g., partitioning into organic matter). The soil sorption of neutral, and hydrophobic compounds is dependent on soil and sediment organic content; one of the useful parameters for describing sorption of neutral, and hydrophobic compounds is the organic carbon partition coefficient (Koc) that is correlated to its Kow(Karickhoff et al., 1979). For successful bioremediation treatment, the pollutants as substrates must be available and accessible either to microorganisms or their extracellular enzymes for metabolism to occur. Another important limiting factor is microbial movement. Because of low bioavailability and accessibility of pollutants, biphasic ('hockey stick') kinetics of biodegradation, consisting of an initial period of fast degradation, followed by a second, much slower phase, is commonly observed in soils and sediments during bioremediation (Semple et al., 2004). These constraints drive a constant demand for developing innovative treatment methods.

4.3.1 Composting

Traditionally, the practice of composting is intended to reduce volume and water content of vegetable wastes, to destroy pathogens, and to remove odor-producing compounds. This technology is now applied for handling polluted soil or sediments by two chief ways: (i) composting of polluted soils for efficient degradation, and (ii) addition of composted materials. Additions of composted material were found to improve degradation of two herbicides, benthiocarb (S-4-chlorobenzyl diethylthiocarbamate) and MCPA (4-chloro-2-methylphenoxyacetic acid) in soil (Duah-Yentumi and Kuwatsuka, 1980). Van Gestel et al. (2003) reported that the impact of diesel on the composting process was negligible when soil was spiked with diesel oil and mixed with biowaste (vegetable, fruit and garden waste) at a 1:10 ratio (fresh weight) and composted in a monitored composting bin system. The spent mushroom waste from ***Pleurotus ostreatus*** was found to degrade and mineralize DDT in soil (Purnomo et al., 2010). On the contrary, Alvey and Crowley (1995)observed that additions of compost suppressed soil mineralization of atrazine relative to rates in unamended soils or in soils amended with starch or rice hulls, probably due to the high nitrogen content of the compost.

The critical parameters for composting depend on the type of contaminants and waste materials to be used for composting. The composting efficiency essentially depends on temperature and soil/waste amendment ratio as the two important operating parameters for bioremediation (Antizar-Ladislao et al., 2005). According to Baheri and Meysami (2002), the increase in the bulking agents such as peat moss, pine wood shavings, bran flakes, or a mixture of these agents from 6 to 12% led to an increase of 4–5% in the biodegradation of total petroleum hydrocarbons. In another study, the soil amendment with sludge-only or compost-only in a ratio of 1:0.1, 1:0.3, 1:0.5, and 1:1 (soil/amendment, wet weight basis) increased the rates, but higher mix ratios did not increase the degradation rates of total petroleum hydrocarbons correspondingly (Namkoong et al., 2002). For the optimum removal of aged PAH during composting, Guerin (2000) recommended to keep moisture and amendment ratio constant. During the composting-bioremediation, not only the contaminant but also the waste amendment and the operating conditions will determine the rate of biodegradation.

Organic pollutants can be degraded during the first phase of rapid decomposition during composting. Heat which is generated by microbial metabolism is trapped in the compost matrix and most of the microbial decomposition and biomass formation occur during the thermophilic stage of composting. The mixing of remediated soil with contaminated soil can increase the effectiveness of composting because the remediated soil with acclimated microorganisms significantly influences pollutant degradation in the composting process (Hwang et al., 2001). The mineralization may be only a small fraction of pollutant degradation, with other prominent fates being partial degradation to secondary compounds, volatilization, and adsorption to compost (Buyuksonmez et al., 1999). In the composting matrices, microorganisms can degrade pollutants into innocuous compounds, transform pollutants into less toxic substances and/or aid in locking up the chemical pollutants within the organic matrix, thereby reducing pollutant bioavailability. Even in the compost remediation strategy, the bioavailability and biodegradability of pollutants are the two most important factors which determine the degradation efficiency (Semple et al., 2001). Cai et al. (2007) showed that the efficiency of composting processes differed among the manually turned compost, inoculated manually turned compost, continuously aerated compost and intermittently aerated compost for bioremediating sewage sludge contaminated with PAHs, with the intermittently aerated compost treatment showing higher removal rate of high molecular weight PAHs. Composting or the use of composted materials can be applied to the bioremediation of polluted soils. However, the nature of waste or soil organic matter that consists of humic materials play an important role in binding of the contaminants such as PAHs and making them accessible to microbes for degradation. Plaza et al. (2009) reported that composting will induce significant modifications to the structural and chemical properties of the humic material fraction including loss of aliphatic materials, an increased polarity and aromatic polycondensation resulting in a decrease in PAH-binding. Recently, Sayara et al. (2010) demonstrated that stable composts in municipal solid wastes enhanced biodegradation of PAH particularly during the initial phase of composting. Humic material which accumulates with an increase in stability of the compost is known to act like a surfactant and plays an important role in releasing PAHs sorbed to the soil. PAH degradation mostly occurs during mesophilic stage of composting, while thermophilic stage is inhibitory for biodegradation (Antizar-Ladislao et al., 2004,Haderlein et al., 2006 and Sayara et al., 2009).

Similar to any other technology, composting has both advantages and limitations. Addition of compost to contaminated soil for bioremediation makes it a sustainable technology since the biodegradable organic waste in the compost is being utilized for beneficial activity. Also, composting improves the soil structure, nutrient status and microbial activity. During composting the contaminant can disappear via different mechanisms such as mineralization by microbial activity, transformation to products, volatilization, and formation of nonextractable bound residues with organic matter. The fate of nonextractable bound residues of contaminants in composting is another area of interest that requires more research into their release, behavior and risk. One of the critical knowledge gaps of composting is lack of sufficient knowledge about microorganisms involved during various stages of composting, the thermophilic stage in particular, which is almost like a blackbox. In fact, there are conflicting views about the role of the thermophilic stage of composting in bioremediation of contaminants. Added to this complexity is the fate of bound residues and whether or not they pose a risk in the future. Knowledge about (a) the nature and activity of microorganisms involved in various stages of composting, and (b) the degree of stability of compost and its humic matter content will greatly assist in better designing of composting as a bioremediation strategy for contaminated soils.

4.3.2 Electrobioremediation

Electrobioremediation as a hybrid technology of bioremediation and electrokinetics for the treatment of hydrophobic organic compounds is becoming popular. It involves passage through polluted soil of a direct current between appropriately distributed electrodes and uses microbiological phenomena for pollutant degradation and electrokinetic phenomena for the acceleration and orientation of transport of pollutants (or their derivatives) and the pollutant-degrading microorganisms (Chilingar et al., 1997 and Li et al., 2010). The electrokinetics is the use of weak electric fields of about 0.2 to 2.0 V cm^{-1} to soil (Saichek and Reddy, 2005) and the basic phenomena which make up electrokinetic remediation are diffusion, electrolysis, electroosmosis, electrophoresis, and electromigration. Since the present electrokinetic approaches mainly aim at pollutant extraction through transport over large distances, the impact of direct current on organism–soil interactions and organism–compound is often neglected (Wick et al., 2007). Shi et al. (2008) showed that direct current (X = 1 V cm^{-1}; J = 10.2 mA cm^{-2}) as typically used for electrobioremediation measures had no negative effect on the activity of a PAH-degrading soil bacterium (***Sphingomonas*** sp. LB126), and the DC-exposed cells exhibited up to 60% elevated intracellular ATP levels and yet remained unaffected on all other levels of cellular integrity and functionality. Information on the direct reduction or oxidation of the pollutant at the electrode and the changes in microbial community due to generation of hydrogen or oxygen at the electrode is limited.

Luo et al. (2005) developed the non-uniform electrokinetic system with periodic polarity-reversal to accelerate the movement and ***in situ*** biodegradation of phenol in a sandy loam soil. Although reversing the polarity of an electric field increased the consumption of electricity, a higher and more uniform removal of phenol from the soil was observed. The 2-dimensional (2-D) non-uniform electric field enhanced the ***in situ*** bioremediation process by promoting the mass transfer of organics to degrading bacteria. When tested at bench-scale with a sandy loam soil and 2,4-dichlorophenol (2,4-DCP) at bidirectional and rotational modes, the 2-D non-uniform electric field stimulated the desorption and the movement of 2,4-DCP. About 73.4% of 2,4-DCP was removed at the bidirectional mode and about 34.8% was removed at the rotational mode, which also maintained remediation uniformity in soil, in 15 days (Fan et al., 2007). In an electrochemical cell packed with an inert support, the application of low intensity electric current led to the degradation of hexadecane as well as higher biomass production by ***Aspergillus niger*** (Velasco-Alvarez et al., 2011).

During electrobioremediation, the transport of PAH-degrading bacteria, ***Sphingomonas*** sp. L138 and ***Mycobacterium frederiksbergense*** LB501 from the surface into the subsurface occurred due to electroosmosis (Wick et al., 2004). Niqui-Arroyo and Ortega-Calvo (2007) integrated biodegradation and electroosmosis for the enhanced removal of PAHs from the creosote-polluted soils. The residual concentrations of total biodegradable PAHs, remaining after bioremediation in soil slurries, were two-fold lower in electrokinetically pretreated soils than in untreated soils. The remediation rate of ***in situ*** bioremediation will be otherwise very slow due to limited mass transfer of pollutants to the degrading bacteria. Very recently, Maillacheruvu and Chinchoud (2011) demonstrated synergistic removal of contaminants by the electrokinetically transported aerobic microbial consortium.

There are limitations with electrobioremediation technology that need to be overcome, and these include: (i) solubility of the pollutant and its desorption from the soil matrix, (ii) the availability of the right type of microorganisms at the site of contamination, (iii) the ratio between target and nontarget ion concentrations, (iv) requirement of a conducting pore fluid to mobilize pollutants, (v) heterogeneity or anomalies found at sites, such as large quantities of iron or iron oxides, large rocks or gravel, and (vi) toxic electrode effects on microbial metabolism or dielectric cell membrane breakdown or changes in the physicochemical surface properties of microbial cells.

4.3.3 Microbe-assisted phytoremediation

Pollutant effects on plant growth are concentration-dependent and different plant species respond differently. Low doses of pollutant can increase plant weight while high doses can inhibit, a phenomenon referred to as 'hormesis' (Calabrese and Blain, 2009). In general, plants can promote dissipation of organic pollutants by immobilization, removal, and promotion of microbial degradation. Some organic compounds are transported across plant membranes, released through leaves via evapotranspiration (phytovolatilization) or extracted, transported and accumulated in plant tissues (phytoextraction) or degraded via enzymatic processes (phytodegradation). Some of the non-volatile compounds are sequestered ***in planta*** and are less bioavailable (phytostabilization). Several limitations of bioremediation such as the inability of degrading microorganisms to compete with indigenous microflora, insufficient microbial activities at sub-surface, poor support of native as well as pollutant-degrading microflora by available or limiting nutrients, heterogeneity of bioavailable contaminants, and toxic or inhibitory compounds in the pollutant mixture requires the union of phytoremediation and other bioremediation strategies (Gerhardt et al., 2009).

Plants have several kilometers of roots per hectare, suggesting the potential of pollutant degradation in the rhizosphere (Boyajian and Carreira, 1997). Sugars, organic acids, and larger organic compounds which constitute about 10–50% of plant's photosynthate are deposited in soils (Kumar et al., 2006), and the carbon cycling from CO_2 assimilation by plants to root exudation to incorporation to microbial biomass to microbial respiration takes about just 5 h (Ostle et al., 2003). In the rhizosphere which is dependent on morphology, proportion of fine roots, water and nutrient conditions, root exudation, and associated microbial communities, there may be either promotion or competition between the pollutant degraders and other microbial members.Ma et al. (2010) suggested from a meta-analysis that the activity of PAH decomposers in soil is more likely to be enhanced by root activities than to be inhibited by other microorganisms in the rhizosphere, despite the variations due to species, habitats, contamination types and doses. The complex aromatic compounds such as flavonoids and coumarins which aid microbial colonization of roots are structurally similar to PCBs, PAHs and PHC, providing opportunities as the analogue-enrichment for stimulating degradative pathways in microorganisms (Holden and Firestone, 1997). Rhizoremediation, an integral component of phytoremediation can occur naturally or can be triggered by introducing specific pollutant-degrading microbes or plant growth promoting microorganisms (Gerhardt et al., 2009). Since the root depth of herbaceous plants varies from plant to plant, from soil to soil, and season to season, the presence of contaminants in soils which is deeper than the root zone of plants requires excavation, other agronomic practices or selection of trees with deeper roots. Nevertheless, most of the recalcitrant organic contaminants are typically found in the top few cm of the soil. Dendroremediation, which is a type of phytoremediation using trees may be useful in attenuating certain pollutants such as 2,4,6-trinitrotoluene and trichloroethylene from soil and groundwater (Susarla et al., 2002).

Plants produce many secondary plant metabolites (SPMEs) which include allelopathic chemicals, root exudates, phytohormones/phytoalexins, phytosiderophores, and phytoanticipins and are derived from isoprenoid, phenylpropanoid, alkaloid or fatty acid/polyketide pathways (Hadacek, 2002). Singer et al. (2004)argued that SPMEs are pollutant analogues within the network of suprametabolism, having implications for predicting the fate of pollutants. Gilbert and Crowley, 1998 and Kim et al., 2003 showed that SPMEs such as limonene, cymene, carvone and pinene enhanced degradation of PCBs. ***Pseudomonas putida*** PCL1444, isolated from the rhizosphere of ***Lolium multiflorum*** cv. Barmultra when grown in PAH-polluted soil degraded the PAHs and protected the plant from the pollutant, by efficient utilization of root exudates for growth and high transcription of naphthalene catabolic genes (Kupier et al., 2002). Narasimhan et al. (2003) applied the rhizosphere metabolomics-driven approach, which has been referred to profiling of root exudates for identification of targeted compounds for creating the nutritional bias, to degrade PCBs (2Cl-biphenyl, 4Cl-biphenyl and Aroclor 1254 at 53 μM) in the rhizosphere of ***Arabidopsis***. The growth of ***gfp***-tagged***Pseudomonas putida*** PML2 was increased due to the exudation of SPMEs such as phenylpropanoids and consequently PCB degradation was enhanced. The rhizosphere metabolomics-driven approach will become an important tool for engineering phytoremediation systems.

The activity and the numbers of the pollutant-degrading endophytes are both plant- and contaminant-dependent (Siciliano et al., 2001). Contaminants such as TCE and methyl ***tert***-butyl ether which are routinely assimilated in the transpiration pathways of plants may be degraded effectively by the pollutant-degrading endophytes. ***Methylobacterium*** sp. strain BJ001, a phytosymbiotic bacterium isolated from tissue culture plantlets of ***Populus deltoides*** × ***nigra*** DN34 was found to transform 2,4,6-trinitrotoluene and mineralize hexahydro-1,3,5-trinitro-1,3,5-triazine and octahydro-1,3,5,7-tetranitro-1,3,5-tetrazocine to CO_2 (Van Aken et al., 2004). Barac et al. (2004) demonstrated that the engineered endophyte (***Burkholderia cepacia*** strain L.S.2.4 containing the toluene-degrading plasmid, pTOM), when applied to surface-sterilized yellow lupine seeds led not only to the protection against the phytotoxic effects of toluene but also decreased emissions from the transpiration stream of its host. The pollutant-degrading endophytes are relatively free from the competition for nutrients and water among the colonizers in the rhizosphere. Greater opportunities for employing the endophyte-assisted phytoremediation, either through naturally-occurring or engineered endophytes exist, especially for the mobile pollutants. Phytostimulation of pollutant degradation by microorganisms in the rhizosphere or inside the plants can offer many economic and environmental advantages compared to the conventional strategies employed in biostimulation. But, the disadvantages include hydrophobicity and chemical stability of pollutants that influence the phytostabilization and the rates of degradation by the associated microorganisms (Van Aken et al., 2010), and plant root exudation which modifies the structure and activities of pollutant-degrading microorganisms (Corgie et al., 2004). Besides, phytoremediation in the field is also challenged by many obstacles which include the inability to mitigate plant stress factors and non-availability of suitable methods for the assessment of phytoremediation (Gerhardt et al., 2009).

4.4 Bioremediation monitoring and efficacy testing

Monitoring and efficacy testing for bioremediation are essential for the purposes of efficiency and economics. There is a strong need to test the efficacy. The 'conservative biomarkers', the internal markers such as dimethyl chrysene which are recalcitrant can be used to test the efficacy of bioremediation (Huang et al., 2005). The concentration of an individual pollutant can be normalized to the internal marker and the relative ratio of a specific pollutant to the internal marker should decrease during the remediation process. Indices such as the carbon preference index, average chain length and various ***n***-alkane/acyclic isoprenoid ratios which are used for the chemical fingerprinting in the environmental forensics can be applied to distinguish the plant- or microbe-derived hydrocarbons from the hydrocarbons of petrogenic or anthropogenic origin. The epicuticular waxes derived from leaf cuticles are generally abundant with odd-numbered ***n***-alkane peaks in the range of C_{25}–C_{31}, while the even-numbered carbon compounds are abundant in petroleum. The carbon preference indices indicating the ratio of odd-numbered to even-numbered carbon compounds provide information on the predominance of phytogenic or petrogenic hydrocarbon contamination (Jeng, 2006).

Several microbiological methods are currently employed for the general soil quality assessment. The monitoring and efficacy testing for bioremediation require a careful selection from them, besides using specific information on abundance of microbial members or genes, and microbial processes and activities since factors such as water content, temperature and many others determine the course of attenuation. The global regulatory networks in which sets of operons, scattered on the bacterial genome and representing disparate functions such as response to nutrient starvation are coordinately controlled in microorganisms (Gottesman, 1984). The signal transduction and effector proteins which are involved in the nitrogen regulation (Reitzer, 2003) or the involvement of ***cra***, ***crp*** and ***relA/spoT*** modulons and the accumulated levels of alarmone guanosine 3′,5′-bis(diphosphate) and cAMP (Hardiman et al., 2007) can be the basis of a means to monitor changes in nutrient limitation of microbial response during the bioremediation process. Many functional genes namely, ***nahAc***, ***alkB*** and ***xylE*** which are involved in the degradation of naphthalenes, ***n***-alkanes and toluene, respectively are known from the cultured microorganisms. With optimized assays, the functional gene abundances which seem to reflect the type as well as the actual degradation rates can be used to assess the efficacy of bioremediation (Salminen et al., 2008). Recently,Kao et al. (2010) used the culture-based method, real-time polymerase chain reaction of genes such as phenol hydroxylase, ring-hydroxylating toluene monooxygenase, naphthalene dioxygenase, toluene monooxygenase, toluene dioxygenase and biphenyl dioxygenase, and denaturing gradient gel electrophoresis fingerprinting analysis for microbial communities to evaluate the effectiveness of bioremediation of a petroleum contaminated site. Compound specific carbon isotope (CSI) analysis has emerged recently as a powerful tool to quantify and/or distinguish biodegradation from other abiotic processes such as sorption, volatilization etc. of contaminants like chlorinated solvents (TCE, PCE, DCE) and aromatic hydrocarbons (benzene, toluene, xylene, ethyl benzene, naphthalene, etc.) and to confirm intrinsic biodegradation during natural attenuation process in the contaminated aquifers (Fischer et al., 2007,Fischer et al., 2008, Hunkeler et al., 2005 and Meckenstock et al., 2004). In stable carbon isotope analysis, the lighter isotope is preferentially utilized by microorganisms leaving behind the heavier isotope thereby resulting in a distinct fractionation pattern among ^{12}C and ^{13}C.

Toxicity testing should be an integral part of the bioremediation program since a reduction in toxicity is a necessary characteristic of bioremediation process. The toxicity of a pollutant to microorganisms is also regarded as a direct measure of bioavailability (Ronday et al., 1997). Megharaj et al. (2000) suggested that chemical analysis in conjunction with bioassays were necessary for toxicological estimations. Despite the importance of toxicological assays, only few bioremediation studies have attempted to include one or two such assays. The toxicity of fuel spills followed by bioremediation treatment was assessed by Microtox measurements, seed germination and plant growth assays (Leung et al., 1997 and Wang and Bartha, 1990). Although the standardized toxicity test system such as Microtox which employs ***Vibrio fischeri***, a bioluminescent marine bacterium, has certain advantages, the ecological relevance of toxicity tests can be improved by use of ecologically relevant (aquatic or terrestrial) representatives from different trophic levels. The efficacy of bioremediation (bioaugmentation with ***Pseudomonas*** sp. strain ADP or biostimulation with citrate) of atrazine-contaminated soils was tested by ecotoxicological endpoints such as plant biomass production, earthworm reproduction, microalgae growth, and cladoceran reproduction (Chelinho et al., 2010). Since no single organism is consistently sensitive to all pollutants, it is pertinent to include a battery of bioassays, by involving members from different trophic levels of the food chain. Every bioremediation technology thus requires the use of experimental controls and performance indicators for both process optimization and implementation of regulatory decisions.

5 Phytoremediation

Phytoremediation is an emerging green technology that uses plants to remediate soil, sediment, surface water, and groundwater environments contaminated with toxic metals, organics, and radionuclides (Pradhan et al., 1998).

Phytoremediation is an effective, non-intrusive, and inexpensive means of remediating soils. It is more cost-effective than alternative mechanical or chemical methods of removing hazardous compounds from the soil. Phytoremediation is a natural, aesthetically pleasing low-cost technology. It is socially accepted by surrounding communities and regulatory agencies as a potentially elegant and beautiful technology.

Although phytoremediation has been employed to remediate environments contaminated with metals, radionuclides, organics, etc. there appear to be many more works on the search for hyperaccumulators of metals than any other topic. In fact, most publications appear to deal with phytoextraction of metal contaminants. Besides, most phytoremediation review papers focus on the phytoextraction of metals and dedicate only a few paragraphs to the phytoremediation of organics.

As overwhelmingly positive results have become available regarding the ability of plants to degrade certain organic compounds, more and more people are getting involved in the phytoremediation of organic contaminants. Actually, the concept of using plants to remediate soils contaminated with organic pollutants is based on observations that disappearance of organic chemicals is accelerated in vegetated soils compared with surrounding nonvegetated bulk soils (Burken and Schnoor, 1996 and Cunningham and Berti, 1993).

Phytoremediation of organic contaminants has generally focused on three classes of compounds: chlorinated solvents, explosives and petroleum hydrocarbons. Nonetheless, in recent years, researchers have begun to address the potential of phytoremediation to treat other organic contaminants including polynuclear aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs).

Although correlations between agronomic performance and phytoremediation potential are yet to be determined, better agronomic performance of the plant may improve phytoremediation. Plants that are less affected by compounds in contaminated soils are healthier and more persistent and will produce healthier root systems and greater top growth.

There are two different strategies for the phytoremediation of organics: ***direct phytoremediation*** and ***phytoremediation explanta*** (Anderson et al., 1993, Cunningham et al., 1995 and Salt et al., 1998). The latter is based on the secretion by plants of their photosynthate in root exudates, which support the growth and metabolic activities of diverse fungal and bacterial communities in the rhizosphere. Some organic compounds in root exudates (i.e., phenolics, organic acids, alcohols, proteins) may serve as carbon and nitrogen sources for growth and long-term survival of microorganisms that are capable of degrading organic pollutants. Densities of rhizospheric bacteria can be as much as two to four orders of magnitude greater than populations in the surrounding bulk soils as well as displaying a greater range of metabolic.

The chemical composition of root exudates and rates of exudation differ considerably among plant species. This has led some research groups to screen for plant species that exude phenols capable of supporting PCB-degrading bacteria (Fletcher and Hedge, 1995 and Salt et al., 1998). Since not all plants produce and release the same types of phenolics (Rao, 1990), it would be expected that some plants may preferentially harbor PCB-degrading (polychlorinated phenols) bacteria in their rhizosphere (Wenzel et al., 1999). Fletcher and Hedge (1995) screened 17 different perennial plants for release of phenols that could support PCB-degrading microbes and found that mulberry (***Morus rubra*** L.) had many attributes that would favor its use in phytoremediation efforts.

Rhizospheric microorganisms may also accelerate remediation processes by volatilizing organics such as PAHs (polynuclear aromatic hydrocarbons) or by increasing the production of humic substances from organic pollutants (Cunningham et al., 1996 and Dec and Bollag, 1994). Similar experiments have been performed to remediate soils contaminated with TCE (trichloroethylene) and TNT (trinitrotoluene).

In addition to secreting organic compounds that support the growth and activities of rhizospheric microorganisms, plants also release a number of enzymes into soils and waters and these enzymes degrade organic contaminants. Soil enzymes derived from plant sources include laccases, dehalogenases, nitroreductases, nitrilases and peroxidases. Field tests of plant-derived nitroreductases and laccases showed significant degradation of ammunition wastes (TNT, dinitromono-aminotoluene, and mononitrodiaminotoluene) and triaminotoluene, respectively (Wolfe et al., 1993). Boyajian and Carreira (1997) reported on the ability of nitroreductase to degrade various additional nitroaromatic compounds. Similarly, other studies have examined the ability of a nitrilase to degrade 4-chlorobenzonitrile and of halogenases to metabolize hexachloroethane and TCE (Wenzel et al., 1999). The degree of enzyme release into soils and sediments remains poorly understood but the measured half-life of these enzymes suggests they may actively degrade soil contaminants for days following their release from plant tissues (Schnoor et al., 1995).

The presence of plant-derived enzymes capable of degrading environmentally problematic xenobiotics will no doubt be exploited for the development of future phytoremediation strategies (Salt et al., 1998).

By analogy with the phytoextraction of metals, direct uptake of organic contaminants is primarily limited by the availability of the target compound and uptake mechanisms (Salt et al., 1998). With a few notable exceptions, movement of organics into plants occurs via the liquid phase of the soil, which has been extensively investigated in plants for uptake of pesticides and herbicides (Briggs et al., 1982, Paterson et al., 1990 and Topp et al., 1986).

The primary factors that govern the uptake of xenobiotics are the physicochemical characteristics of the compound, i.e., the octanol-water partition coefficient, log K_{ow}, acidity constant, pK_a, concentration and others (Wenzel et al., 1999). Organics that are most likely to be taken up by plants are moderately hydrophobic compounds with octanol–water partition coefficients ranging from 0.5 to 3 (Briggs et al., 1982,Ryan et al., 1988 and Wenzel et al., 1999). In addition to factors that govern the bioavailability of organics for uptake, there appears to be a significant disparity in the uptake and translocation of organics among plant species, as observed for nitrobenzene (MacFarlane et al., 1990) and atrazine (Anderson and Walton, 1995 and Burken and Schnoor, 1996). Differences in evapotranspiration rates that are known to have a marked effect on the contaminant uptake could explain these differences.

As mentioned above, bioavailability of organics in soils appears to be a primary restriction for effective phytoremediation of organic pollutants (Cunningham et al., 1996, Schnoor et al., 1995 and Salt et al., 1998). The application of soil amendments has been considered a major breakthrough in the development of "induced" (as opposed to "continuous") metal phytoextraction strategies. Unfortunately, similar attempts have not been made in relation to organic uptake of plants. The use of synthetic (triton X-100, SDS) and naturally-produced biosurfactants (rhamnolipids) to enhance the apparent water solubility and bacterial degradation of organic contaminants is well documented (Bragg et al., 1994, Desai and Banat, 1997,Providenti et al., 1995, Van Dyke et al., 1993 and Zajic and Panchel, 1976). It has also been reported (Brusseau et al., 1997) that cyclodextrins increase the solubilities of both organics and metals. Potential advantages of using biosurfactants or cyclodextrins which have the ability to solubilize both organics and metals (Miller, 1995 and Nivas et al., 1996) could be instrumental in remediation of soils with mixed contaminants.

If plants are to be used for phytoextraction of organic contaminants it is essential to determine the fate of the parent compounds and their metabolites. The partitioning of organics between roots and aboveground tissues varies considerably depending on the chemical in question. Following uptake, organic compounds may have multiple fates: they may be translocated to other plant tissues and subsequently volatilized, they may undergo partial or complete degradation or they may be transformed to less toxic compounds and bound in plant tissues to nonavailable forms. Schroll et al. (1994) found that hexachlorobenzene (HBC) and octachlorodibenzo-p-dioxin (OCDD) could be taken up by roots or leaves but that no translocation from roots to shoots or vice versa was observed. On the other hand, root and foliar uptake of the herbicides chlorobenzene and trichloroacetic (TCA) was followed by translocation in both directions (Wenzel et al., 1999). Preferential concentration in the roots has also been documented for TNT and aniline and in shoots for hexahydro-1,3,5-trinitro-1,3,5-trizazine (RDX), phenol, and quinoline following uptake by roots (Cataldo et al., 1987, Fellows et al., 1996 and Wenzel et al., 1999).

Most organics appear to undergo some degree of transformation in plant cells before being sequestered in vacuoles or bound to insoluble cellular structures, such as lignin (Salt et al., 1998). However, few chemicals appear to be fully mineralized by plants to water and CO_2, and where this does occur, it represents only a small percentage of the total parent compound (Newman et al., 1997). This property puts plants at a relative disadvantage compared with bacteria in degrading organic pollutants. In addition, the possibility that plant metabolites of pollutants may be more toxic than the original pollutants creates a difficult regulatory environment for remediation of organics.

6 METAL REMOVAL

6.1 Problem

Metals contamination is a persistent problem at many contaminated sites, approximately 75% of contaminated areas face that problem. The most commonly occurring metals at these sites are lead (Pb), chromium (Cr), arsenic (As), zinc (Zn), cadmium (Cd), copper (Cu), and mercury (Hg). Figure 1 summarizes the frequency with which these metals occur at restoration sites in USA.

The presence of metals in groundwater and soils can pose a significant threat to human health and ecological systems. The chemical form of the metal contaminant influences its solubility, mobility, and toxicity in ground-water systems. The chemical form of metals depends on the source of the metal waste and the soil and ground-water chemistry at the site. A detailed site characterization must be performed to assess the type and level of metals present and allow evaluation of remedial alternatives.

Typically metals are relatively immobile in subsurface systems as a result of precipitation or adsorption reactions. For this reason, remediation activities at metals-contaminated sites have focused on the solid-phase sources of metals, i.e., contaminated soils, sludges, wastes, or debris. A range of technologies is available for remediation of metals-contaminated soil and groundwater at contaminated sites. General approaches to remediation of metal contamination include isolation, immobilization, toxicity reduction, physical separation and extraction. These general approaches can be used for many types of contaminants but the specific technology selected for treatment of a metals-contaminated site will depend on the form of the contamination and other site-specific characteristics. One or more of these approaches are often combined for more cost-effective treatment. A number of the available technologies have been demonstrated in full-scale applications and are presently commercially available. A comprehensive list of these technologies is available (U.S. EPA, 1996). Several other technologies are being tested for application to metals-contaminated sites.

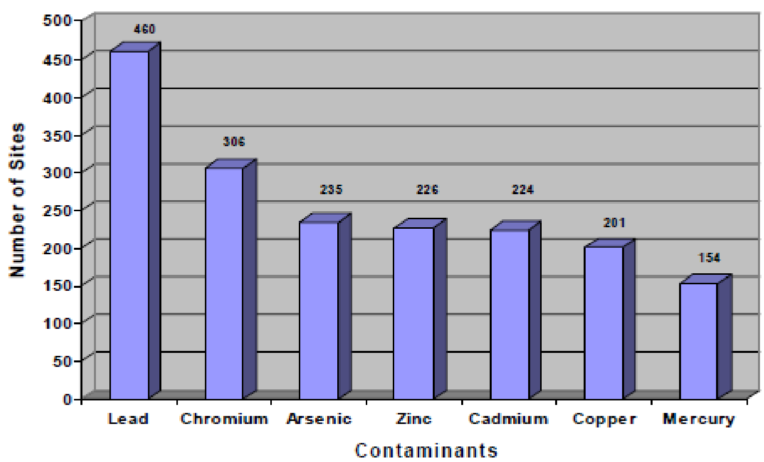

Figure 1. Metals Most Commonly Present in all Matrices at Superfund Sites (from u.s. EPA, 1996).

6.2 Sources of contaminants

Surface water and groundwater may be contaminated with metals from wastewater discharges or by direct contact with metals-contaminated soils, sludges, mining wastes, and debris. Metal-bearing solids at contaminated sites can originate from a wide variety of sources in the form of airborne emissions, process solid wastes, sludges or spills. The contaminant sources influence the heterogeneity of contaminated sites on a macroscopic and microscopic scale. Variations in contaminant concentration and matrix influence the risks associated with metal contamination and treatment options.

6.2.1 Airborne Sources

Airborne sources of metals include stack or duct emissions of air, gas, or vapor streams, and fugitive emissions such as dust from storage areas or waste piles. Metals from airborne sources are generally released as particulates contained in the gas stream. Some metals such as arsenic, cadmium, and lead can also volatilize during high-temperature processing. These metals will convert to oxides and condense as fine particulates unless a reducing atmosphere is maintained (Smith et al., 1995).

Stack emissions can be distributed over a wide area by natural air currents until dry and/or wet precipitation mechanisms remove them from the gas stream. Fugitive emissions are often distributed over a much smaller area because emissions are made near the ground. In general, contaminant concentrations are lower in fugitive emissions compared to stack emissions. The type and concentration of metals emitted from both types of sources will depend on site-specific conditions.

6.2.2 Process Solid Wastes

Process solid wastes can result from a variety of industrial processes. These metal-bearing solid wastes are disposed above ground in waste piles or below ground or under cover in landfills. Examples of process solid wastes include slags, fly ash, mold sands, abrasive wastes, ion exchange resins, spent catalysts, spent activated carbon, and refractory bricks (Zimmerman and Coles, 1992). The composition of the process waste influences the density, porosity, and leach resistance of the waste and must be considered in evaluating the contaminated matrix.

Because waste piles are above ground, they are exposed to weathering which can disperse the waste pile to the surrounding soil, water and air and can result in generation of leachate which infiltrates into the subsurface environment. The ability of landfills to contain process solid wastes varies due to the range of available landfill designs. Uncontained landfills can release contaminants into infiltrating surface water or groundwater or via wind and surface erosion.

6.2.3 Sludges

The composition of sludges depends on the original waste stream and the process from which it was derived. Sludges resulting from a uniform wastestream, such as wastewater treatment sludges, are typically more homogeneous and have more uniform matrix characteristics. Sludge pits, on the other hand, often contain a mixture of wastes that have been aged and weathered, causing a variety of reactions to occur. Sludge pits often require some form of pretreatment before wastes can be treated or recycled (Smith et al., 1995).

6.2.4 Soils

Soil consists of a mixture of weathered minerals and varying amounts of organic matter. Soils can be contaminated as a result of spills or direct contact with contaminated waste streams such as airborne emissions, process solid wastes, sludges, or leachate from waste materials. The solubility of metals in soil is influenced by the chemistry of the soil and groundwater (Sposito, 1989; Evans, 1989). Factors such as pH, Eh, ion exchange capacity, and complexation/chelation with organic matter directly affect metal solubility.

6.2.5 Direct Ground-Water Contamination

Groundwater can be contaminated with metals directly by infiltration of leachate from land disposal of solid wastes, liquid sewage or sewage sludge, leachate from mine tailings and other mining wastes, deep-well disposal of liquid wastes, seepage from industrial waste lagoons, or from other spills and leaks from industrial metal processing facilities (e.g., steel plants, plating shops, etc.). A variety of reactions may occur which influence the speciation and mobility of metal contaminants including acid/base, precipitation/dissolution, oxidation/ reduction, sorption or ion exchange. Precipitation, sorption, and ion exchange reactions can retard the movement of metals in groundwater. The rate and extent of these reactions will depend on factors such as pH, Eh, complexation with other dissolved constituents, sorption and ion exchange capacity of the geological materials, and organic matter content. Ground-water flow characteristics also influence the transport of metal contaminants.

6.3 Chemical fate and mobility

The fate and transport of a metal in soil and groundwater depends significantly on the chemical form and speciation of the metal (Allen et al., 1991). The mobility of metals in ground-water systems is hindered by reactions that cause metals to adsorb or precipitate, or chemistry that tends to keep metals associated with the solid phase and prevent them from dissolving. These mechanisms can retard the movement of metals and also provide a long-term source of metal contaminants (NRC, 1994). While the various metals undergo similar reactions in a number of aspects, the extent and nature of these reactions varies under particular conditions. In Figure 2, for example, the extent of sorption of several metal cations and anions onto iron oxide is shown as a function of pH for a particular background electrolyte composition. It may be seen there that lead sorbs extensively at much lower pH values than zinc or cadmium (Kinniburgh et al., 1976).

The chemical form and speciation of some of the more important metals found at contaminated sites are discussed below. The influence of chemical form on fate and mobility of these compounds is also discussed.

6.3.1 Pb

The primary industrial sources of lead (Pb) contamination include metal smelting and processing, secondary metals production, lead battery manufacturing, pigment and chemical manufacturing, and lead-contaminated wastes. Widespread contamination due to the former use of lead in gasoline is also of concern. Lead released to groundwater, surface water and land is usually in the form of elemental lead, lead oxides and hydroxides, and leadmetal oxyanion complexes (Smith et al., 1995).

Lead occurs most commonly with an oxidation state of 0 or +II. Pb(II) is the more common and reactive form of lead and forms mononuclear and polynuclear oxides and hydroxides. Under most conditions Pb2+ and lead-hydroxy complexes are the most stable forms of lead (Smith et al., 1995). Low solubility compounds are formed by complexation with inorganic (Cl^-, CO_3^{2-}, SO_4^{2-}, PO_4^{3-}) and organic ligands (humic and fulvic acids, EDTA, amino acids) (Bodek et al., 1988). Lead carbonate solids form above pH 6 and PbS is the most stable solid when high sulfide concentrations are present under reducing conditions.

Most lead that is released to the environment is retained in the soil (Evans, 1989). The primary processes influencing the fate of lead in soil include adsorption, ion exchange, precipitation, and complexation with sorbed organic matter. These processes limit the amount of lead that can be transported into the surface water or groundwater. The relatively volatile organolead compound tetramethyl lead may form in anaerobic sediments as a result of alkyllation by microorganisms (Smith et al., 1995).

The amount of dissolved lead in surface water and groundwater depends on pH and the concentration of dissolved salts and the types of mineral surfaces present. In surface water and ground-water systems, a significant fraction of lead is undissolved and occurs as precipitates ($PbCO_3$, Pb_2O, $Pb(OH)_2$, $PbSO_4$), sorbed ions or surface coatings on minerals, or as suspended organic matter.

6.3.2 Cr

Chromium(Cr) is one of the less common elements and does not occur naturally in elemental form, but only in compounds. Chromium is mined as a primary ore product in the form of the mineral chromite, $FeCr_2O_4$. Major sources of Cr contamination include releases from electroplating processes and the disposal of chromium containing wastes (Smith et al., 1995).

Cr(VI) is the form of chromium commonly found at contaminated sites. Chromium can also occur in the +III oxidation state, depending on pH and redox conditions. Cr (VI) is the dominant form of chromium in shallow aquifers where aerobic conditions exist. Cr(VI) can be reduced to Cr(III) by soil organic matter, S^{2-} and Fe^{2+} ions under anaerobic conditions often encountered in deeper groundwater. Major Cr(VI) species include chromate (CrO_4^{2-}) and dichromate ($Cr_2O_7^{2-}$) which precipitate readily in the presence of metal cations (especially Ba^{2+}, Pb^{2+}, and Ag^+). Chromate and dichromate also adsorb on soil surfaces, especially iron and aluminum oxides. Cr(III) is the dominant form of chromium at low pH (<4). Cr^{3+} forms solution complexes with NH_3, OH^-, Cl^-, F^-, CN^-, SO_4^{2-}, and soluble organic ligands. Cr(VI) is the more toxic form of chromium and is also more mobile. Cr(III) mobility is decreased by adsorption to clays and oxide minerals below pH 5 and low solubility above pH 5 due to the formation of $Cr(OH)_3$(s) (Chrotowski et al., 1991).

Chromium mobility depends on sorption characteristics of the soil, including clay content, iron oxide content and the amount of organic matter present. Chromium can be transported by surface runoff to surface waters in its soluble or precipitated form. Soluble and unadsorbed chromium complexes can leach from soil into groundwater. The leachability of Cr(VI) increases as soil pH increases. Most of chromium released into natural waters is particle associated, however, and is ultimately deposited into the sediment (Smith et al., 1995).

6.3.3 As

Arsenic (As) is a semimetallic element that occurs in a wide variety of minerals, mainly as As_2O_3, and can be recovered from processing of ores containing mostly copper, lead, zinc, silver and gold. It is also present in ashes from coal combustion. Arsenic exhibits fairly complex chemistry and can be present in several oxidation states (-III, 0, III, V) (Smith et al., 1995).

In aerobic environments, As(V) is dominant, usually in the form of arsenate (AsO_4^{3-}) in various protonation states: H_3AsO_4, $H_2AsO_4^-$, $HAsO_4^{2-}$, AsO_4^{3-}. Arsenate, and other anionic forms of arsenic behave as chelates and can precipitate when metal cations are present (Bodek et al., 1988). Metal arsenate complexes are stable only under certain conditions.

As(V) can also coprecipitate with or adsorb onto iron oxyhydroxides under acidic and moderately reducing conditions. Coprecipitates are immobile under these conditions but arsenic mobility increases as pH increases (Smith et al., 1995).

Under reducing conditions As(III) dominates, existing as arsenite (AsO_3^{3-}) and its protonated forms: H_3AsO_3, $H_2AsO_3^-$, $HAsO_3^{2-}$. Arsenite can adsorb or coprecipitate with metal sulfides and has a high affinity for other sulfur compounds. Elemental arsenic and arsine, AsH_3, may be present under extreme reducing conditions.

Biotransformation (via methylation) of arsenic creates methylated derivatives of arsine, such as dimethyl arsine $HAs(CH_3)_2$ and trimethylarsine $As(CH_3)_3$ which are highly volatile.

Since arsenic is often present in anionic form, it does not form complexes with simple anions such as Cl^- and SO_4^{2-}. Arsenic speciation also includes organometallic forms such as methylarsinic acid $(CH_3)AsO_2H_2$ and dimethylarsinic acid $(CH_3)_2AsO_2H$. Many arsenic compounds sorb strongly to soils and are therefore transported only over short distances in groundwater and surface water. Sorption and coprecipitation with hydrousiron oxides are the most important removal mechanisms under most environmental conditions (Krause and Ettel, 1989; Pierce and Moore, 1982). Arsenates can be leached easily if the amount of reactive metal in the soil is low. As(V) can also be mobilized under reducing conditions that encourage the formation of As(III), under alkaline and saline conditions, in the presence of other ions that compete for sorption sites, and in the presence of organic compounds that form complexes with arsenic (Smith et al., 1995).

6.3.4 Zn

Zinc (Zn) does not occur naturally in elemental form. It is usually extracted from mineral ores to form zinc oxide (ZnO). The primary industrial use for Zinc is as a corrosion-resistant coating for iron or steel (Smith et al., 1995).

Zinc usually occurs in the +II oxidation state and forms complexes with a number of anions, amino acids and organic acids. Zn may precipitate as $Zn(OH)_2$(s), $ZnCO_3$(s), ZnS(s), or $Zn(CN)_2$(s). Zinc is one of the most mobile heavy metals in surface waters and groundwater because it is present as soluble compounds at neutral and acidic pH values. At higher pH values, zinc can form carbonate and hydroxide complexes which control zinc solubility. Zinc readily precipitates under reducing conditions and in highly polluted systems when it is present at very high concentrations, and may coprecipitate with hydrous oxides of iron or manganese (Smith et al., 1995).

Sorption to sediments or suspended solids, including hydrous iron and manganese oxides, clay minerals, and organic matter, is the primary fate of zinc in aquatic environments. Sorption of zinc increases as pH increases and salinity decreases.

6.3.5 Cd

Cadmium (Cd) occurs naturally in the form of CdS or $CdCO_3$. Cadmium is recovered as a by-product from the mining of sulfide ores of lead, zinc and copper. Sources of cadmium contamination include plating operations and the disposal of cadmium-containing wastes (Smith et al., 1995).

The form of cadmium encountered depends on solution and soil chemistry as well as treatment of the waste prior to disposal The most common forms of cadmium include Cd^{2+}, cadmium-cyanide complexes, or $Cd(OH)_2$ solid sludge (Smith et al., 1995). Hydroxide ($Cd(OH)_2$) and carbonate ($CdCO_3$) solids dominate at high pH whereas Cd^{2+} and aqueous sulfate species are the dominant forms of cadmium at lower pH (<8). Under reducing conditions when sulfur is present, the stable solid CdS(s) is formed. Cadmium will also precipitate in the presence of phosphate, arsenate, chromate and other anions, although solubility will vary with pH and other chemical factors.

Cadmium is relatively mobile in surface water and ground-water systems and exists primarily as hydrated ions or as complexes with humic acids and other organic ligands (Callahan et al., 1979). Under acidic conditions, cadmium may also form complexes with chloride and sulfate. Cadmium is removed from natural waters by precipitation and sorption to mineral surfaces, especially oxide minerals, at higher pH values (>pH 6). Removal by these mechanisms increases as pH increases. Sorption is also influenced by the cation exchange capacity (CEC) of clays, carbonate minerals, and organic matter present in soils and sediments. Under reducing conditions, precipitation as CdS controls the mobility of cadmium (Smith et al., 1995).

6.3.6 Cu

Copper (Cu) is mined as a primary ore product from copper sulfide and oxide ores. Mining activities are the major source of copper contamination in groundwater and surface waters. Other sources of copper include algicides, chromated copper arsenate (CCA) pressuretreated lumber, and copper pipes. Solution and soil chemistry strongly influence the speciation of copper in ground-water systems. In aerobic, sufficiently alkaline systems, $CuCO_3$ is the dominant soluble copper species. The cupric ion, Cu^{2+}, and hydroxide complexes, $CuOH^+$ and $Cu(OH)_2$, are also commonly present. Copper forms strong solution complexes with humic acids. The affinity of Cu for humates increases as pH increases and ionic strength decreases. In anaerobic environments, when sulfur is present CuS(s) will form.

Copper mobility is decreased by sorption to mineral surfaces. Cu^{2+} sorbs strongly to mineral surfaces over a wide range of pH values (Dzombak and Morel, 1990). The cupric ion (Cu^{2+}) is the most toxic species of copper. Copper toxicity has also been demonstrated for $CuOH^{+}$ and $Cu_2(OH)_2^{2+}$ (LaGrega et al., 1994).

6.3.7 Hg

The primary source of mercury is the sulfide ore cinnabar. Mercury (Hg) is usually recovered as a by-product of ore processing (Smith et al., 1995). Release of mercury from coal combustion is a major source of mercury contamination. Releases from manometers at pressure measuring stations along gas/oil pipelines also contribute to mercury contamination. After release to the environment, mercury usually exists in mercuric (Hg^{2+}), mercurous (Hg_2^{2+}), elemental (Hg^{o}), or alkyllated form (methyl/ethyl mercury). The redox potential and pH of the system determine the stable forms of mercury that will be present. Mercurous and mercuric mercury are more stable under oxidizing conditions. When mildly reducing conditions exist, organic or inorganic mercury may be reduced to elemental mercury, which may then be converted to alkyllated forms by biotic or abiotic processes. Mercury is most toxic in its alkyllated forms which are soluble in water and volatile in air (Smith et al., 1995).

Hg(II) forms strong complexes with a variety of both inorganic and organic ligands, making it very soluble in oxidized aquatic systems (Bodek et al., 1988). Sorption to soils, sediments, and humic materials is an important mechanism for removal of mercury from solution. Sorption is pH-dependent and increases as pH increases. Mercury may also be removed from solution by coprecipitation with sulfides (Smith et al., 1995).

Under anaerobic conditions, both organic and inorganic forms of mercury may be converted to alkyllated forms by microbial activity, such as by sulfur-reducing bacteria. Elemental mercury may also be formed under anaerobic conditions by demethylation of methyl mercury, or by reduction of Hg(II). Acidic conditions ($pH<4$) also favor the formation of methyl mercury, whereas higher pH values favor precipitation of HgS(s) (Smith et al., 1995).

6.4 Available technologies

6.4.1 Site characterization and establishment of remediation goals

The physical and chemical form of the metal contaminant in soil or water strongly influences the selection of the appropriate remediation treatment approach. Information about the physical characteristics of the site and the type and level of contamination at the site must be obtained to enable accurate assessment of site contamination and remedial alternatives.

The importance of adequate, well-planned site characterization to selection of an appropriate cost-effective remediation approach has been discussed many times (e.g., CII, 1995) but cannot be overemphasized. The contamination in the groundwater and soil should be characterized to establish the type, amount, and distribution of contaminants across different media.

Once the site has been characterized, the desired level of each contaminant in soil and groundwater must be determined. This is done by comparison of observed contaminant concentrations with soil and ground-water quality standards for a particular regulatory domain, or by performance of a site-specific risk assessment. Remediation goals for metals may be set as desired concentrations in groundwater, as total metal concentration in soil, as leachable metal in soil, or as some combination of these.

6.4.2 General remediation approaches

Several technologies exist for the remediation of metals-contaminated soil and water. These technologies are contained within five categories of general approaches to remediation: isolation, immobilization, toxicity reduction, physical separation and extraction. These are the same general approaches used for many types of contaminants in the subsurface (LaGrega et al., 1994). As is usually the case, combinations of one or more of these approaches are often used for more cost-effective treatment of a contaminated site.

Isolation

Isolation technologies attempt to prevent the transport of contaminants by containing them within a designated area. These technologies can be used to prevent further contamination of groundwater when other treatment options are not physically or economically feasible for a site. Contaminated sites may also be isolated temporarily in order to limit transport during site assessment and site remediation.

A) Capping

Capping systems are used to provide an impermeable barrier to surface water infiltration to contaminated soil for prevention of further release of contaminants to the surrounding surface water or groundwater. Secondary objectives include controlling gas and odor emissions, improving aesthetics, and providing a stable surface over a contaminated site.

Capping also eliminates risks associated with dermal contact and/or incidental ingestion of surface soils, but if this is the primary goal for the site and surface water infiltration is not a concern, a less expensive permeable cover may be preferred.

Capping provides a range of design options that includes simple single-layer caps and more complex multilayer systems (Rumer and Ryan, 1995; U.S. EPA, 1991). Design selection depends on site characteristics, remedial objectives and risk factors associated with the site. A variety of materials are available for use in capping systems and choice of materials is site specific because local soils are often incorporated into parts of the cap.

Synthetic membranes such as high-density polyethylene are also available for incorporation into capping systems. Surface water controls, such as ditches and dikes are usually included to help control drainage from the cap. Multilayered capping systems may also include a hard cover and/or a layer of topsoil to separate the underlying layers from the ground surface. Revegetation is promoted in order to reinforce the topsoil, to reduce soil erosion and runoff velocity, and to help remove water from the soil by evapotranspiration (Rumer and Ryan, 1995).

B) Subsurface Barriers

Subsurface barriers may be used to isolate contaminated soil and water by controlling the movement of groundwater at a contaminated site. These barriers are designed to reduce the movement of contaminated groundwater from the site, or to restrict the flow of uncontaminated groundwater through the contaminated site (Rumer and Ryan, 1995).

Vertical barriers are commonly used to restrict the lateral flow of groundwater. For effective isolation of the contaminated matrix, the barrier should extend and key into a continuous, low-permeability layer, such as clay or competent bedrock, below the contaminated area (U.S. EPA, 1985; Rumer and Ryan, 1995). If an impermeable layer is not available, a ground-water extraction system must be used to prevent transport of contaminants under the barrier. Vertical barriers may be installed upstream, downstream, or completely surrounding the site and are often implemented in conjunction with a capping system to control surface water infiltration. The use of circumferential barriers can prevent the escape of contamination from the site by using an infiltration barrier and collection system to create

a hydraulic gradient in the inward direction. Vertical barriers are often limited to depths achievable with backhoe excavation technology for trenches, i.e., to about 10 m (U.S. EPA, 1985).

Slurry walls are usually constructed in a vertical trench excavated under a slurry that is designed to prevent collapse and to form a filter cake on the walls of the trench to prevent the loss of fluids to the surrounding soil (Xanthakos, 1979). A vibrating beam method (Slurry Systems, Inc.) is also available in which the beam penetrates the ground and slurry materials are injected into the soil (with assistance from a high pressure/low volume jet if needed). Two options exist for the slurry composition. The soil-bentonite (SB) slurry wall is the most common type, and comprises a bentonite-water slurry that is mixed with a soil engineered to harden upon addition to the slurry (Rumer and Ryan, 1995). The trench can also be excavated under a portland cement-bentonite-water slurry that is left to harden and form a cement-bentonite (CB) slurry wall (LaGrega et al., 1994). Available technologies for installation of slurry walls allow installation to depths up to 40 m.

Slurry walls are the most common type of vertical barrier due to their low relative cost. The use of slurry walls can be limited by the topography, geology, and type of contamination at the site. For example, an SB slurry will flow unless the site and confining layer are nearly level. Also, some contaminants, such as concentrated organics and strong acids/bases, can degrade SB materials and prevent the application of SB slurry walls at some sites (Rumer and Ryan, 1995).

Other available vertical barriers include grout curtains and sheet piles. Grout curtains are constructed by drilling a borehole and injecting a fluid into the surrounding soil that is designed to solidify and reduce water flow through the contaminated region (U.S. EPA, 1985). The fluid is pressure-injected in rows of staggered boreholes that are designed to overlap once the fluid has permeated into the surrounding soil. Common materials used to construct grout curtains include cement, clays, alkali-silicate, and organic polymers (Rumer and Ryan, 1995). Clays are the most widely used grouting materials due to their low cost. This technique is more expensive than slurry walls and its use is therefore usually limited to sealing voids in existing rock.

Sheet piles usually comprise steel pilings that are driven into the formation to create a wall to contain the groundwater. Sheet piles are seldom used at contaminated sites due to concerns about wall integrity. This method is generally limited to isolation of shallow contamination (12-15 m) distributed over a relatively small area (U.S. EPA, 1985), or used in conjunction with a soil-bentonite slurry when site conditions prevent the use of conventional slurry walls (Rumer and Ryan, 1995).

Technologies for the construction of horizontal barriers are under investigation. Horizontal barriers would enable control of the downward migration of contaminants by lining the site without requiring excavation of the contaminated matrix. The technologies under investigation include grout injection by vertical boring and horizontal drilling. The vertical boring method is similar to the construction of grout curtains except that the grout is injected at a fixed elevation over a tightly spaced grid of vertical boreholes to create an impermeable horizontal layer. Problems with this method include soil compaction by the large drill rigs situated over the contaminated area. Also, the vertical boreholes would provide access to the deeper layers and may therefore increase vertical migration of contaminants. Horizontal drilling involves the use of directional drilling techniques to create the horizontal grout layer.

Horizontal barriers may also be used in conjunction with vertical barriers at sites where a natural aquitard is not present. In this case, the vertical barrier could key into the horizontal barrier to prevent the transport of contaminants under the vertical barrier (Smith et al., 1995).

Immobilization

Immobilization technologies are designed to reduce the mobility of contaminants by changing the physical or leaching characteristics of the contaminated matrix. Mobility is usually decreased by physically restricting contact between the contaminant and the surrounding groundwater, or by chemically altering the contaminant to make it more stable with respect to dissolution in groundwater. The aqueous and solid phase chemistry of metals is conducive to immobilization by these techniques. A variety of methods are available for immobilization of metal contaminants, including those that use chemical reagents and/or thermal treatment to physically bind the contaminated soil or sludge. Most immobilization technologies can be performed ex situ or in situ. In situ processes are preferred due to the lower labor and energy requirements, but implementation in situ will depend on specific site conditions.

A) Solidification/Stabilization

Solidification and stabilization (S/S) immobilization technologies are the most commonly selected treatment options for metals-contaminated sites (Conner, 1990). Solidification involves the formation of a solidified matrix that physically binds the contaminated material.

Stabilization, also referred to as fixation, usually utilizes a chemical reaction to convert the waste to a less mobile form. The general approach for solidification/ stabilization treatment processes involves mixing or injecting treatment agents to the contaminated soils. Inorganic binders, such as cement, fly ash, or blast furnace slag, and organic binders such as bitumen are used to form a crystalline, glassy or polymeric framework around the waste. The dominant mechanism by which metals are immobilized is by precipitation of hydroxides within the solid matrix (Bishop et al., 1982; Shively et al., 1986).

S/S technologies are not useful for some forms of metal contamination, such as species that exist as anions (e.g., Cr(VI), arsenic) or metals that don't have low-solubility hydroxides (e.g., mercury). S/S may not be applicable at sites containing wastes that include organic forms of contamination, especially if volatile organics are present. Mixing and heating associated with binder hydration may release organic vapors. Pretreatment, such as air stripping or incineration, may be used to remove the organics and prepare the waste for metal stabilization/solidification (Smith et al., 1995). The application of S/S technologies will also be affected by the chemical composition of the contaminated matrix, the amount of water present, and the ambient temperature. These factors can interfere with the solidification/stabilization process by inhibiting bonding of the waste to the binding material, retarding the setting of the mixtures, decreasing the stability of the matrix, or reducing the strength of the solidified area (U.S. EPA, 1990b).

Cement-based binders and stabilizers are common materials used for implementation of S/S technologies (Conner, 1990). Portland cement, a mixture of Ca-silicates, aluminates, aluminoferrites, and sulfates is an important cement-based material. Pozzolanic materials which consist of small spherical particles formed by coal combustion (such as fly ash) and in lime and cement kilns, are also commonly used for S/S. Pozzolans exhibit cement-like properties, especially if the silica content is high. Portland cement and pozzolans can be used alone or together to obtain optimal properties for a particular site (U.S. EPA, 1989).

Organic binders may also be used to treat metals through polymer microencapsulation. This process uses organic materials such as bitumen, polyethylene, paraffins, waxes and other polyolefins as thermoplastic or thermosetting resins. For polymer encapsulation, the organic materials are heated and mixed with the contaminated matrix at elevated temperatures (120° to 200°C). The organic materials polymerize, agglomerate the waste and the waste matrix is encapsulated (U.S. EPA, 1989). Organics are volatilized and collected and the treated material is extruded for disposal or possible reuse (e.g., as paving material) (Smith et al., 1995). The contaminated material may require pretreatment to separate rocks and debris and dry the feed material. Polymer encapsulation requires more energy and more complex equipment than cement-based S/S operations. Bitumen (asphalt) is the cheapest and most common thermoplastic binder (U.S. EPA, 1989).

S/S is achieved by mixing the contaminated material with appropriate amounts of binder/stabilizer and water. The mixture sets and cures to form a solidified matrix and contain the waste. The cure time and pour characteristics of the mixture and the final properties of the hardened cement depend upon the composition (amount of cement, pozzolan, water) of the binder/stabilizer.

Ex situ S/S can be easily applied to excavated soils because methods are available to provide the vigorous mixing needed to combine the binder/stabilizer with the contaminated material. Pretreatment of the waste may be necessary to screen and crush large rocks and debris. Mixing can be performed via in-drum, in-plant or area mixing processes. In-drum mixing may be preferred for treatment of small volumes of waste or for toxic wastes. Inplant processes utilize rotary drum mixers for batch processes or pug mill mixers for continuous treatment. Larger volumes of waste may be excavated and moved to a contained area for area mixing. This process involves layering the contaminated material with the stabilizer/binder, and subsequent mixing with a backhoe or similar equipment. Mobile and fixed treatment plants are available for ex situ S/S treatment. Smaller pilot-scale plants can treat up to 100 tons of contaminated soil per day, while larger portable plants typically process 500 to over 1000 tons per day (Smith et al., 1995).

S/S techniques are available to provide mixing of the binder/stabilizer with the contaminated soil in situ. In situ S/S is less labor and energy intensive than ex situ process that require excavation, transport and disposal of the treated material. In situ S/S is also preferred if volatile or semi volatile organics are present because excavation would expose these contaminants to the air (U.S. EPA, 1990a). However the presence of bedrock, large boulders, cohesive soils, oily sands and clays may preclude the application of in situ S/S at some sites. It is also more difficult to provide uniform and complete mixing through in situ processes.

Mixing of the binder and contaminated matrix may be achieved using in-place mixing, vertical auger mixing or injection grouting. In-place mixing is similar to ex situ area mixing except that the soil is not excavated prior to treatment. The in situ process is useful for treating surface or shallow contamination and involves spreading and mixing the binders with the waste using conventional excavation equipment such as draglines, backhoes or clamshell buckets. Vertical auger mixing uses a system of augers to inject and mix the binding reagents with the waste. Larger (2-4 m diameter) augers are used for shallow (3-12 m) drilling and can treat 500-1000 m^3 per day (Ryan and Walker, 1992; Jasperse and Ryan, 1992). Deep stabilization/solidification (up to 45 m) can be achieved by using ganged augers (up to 1 m in diameter each) that can treat 150-400 m^3 per day. Finally injection grouting may be performed to inject the binder containing suspended or dissolved reagents into the treatment area under pressure. The binder permeates the surrounding soil and cures in place (Smith et al., 1995).

B) Vitrification

The mobility of metal contaminants can be decreased by high-temperature treatment of the contaminated area that results in the formation of vitreous material, usually an oxide solid. During this process, the increased temperature may also volatilize and/or destroy organic contaminants or volatile metal species (such as Hg) that must be collected for treatment or disposal. Most soils can be treated by vitrification and a wide variety of inorganic and organic contaminants can be targeted. Vitrification may be performed ex situ or in situ, although in situ processes are preferred due to the lower energy requirements and cost (U.S. EPA, 1992a).

Typical stages in ex situ vitrification processes may include excavation, pretreatment, mixing, feeding, melting and vitrification, off-gas collection and treatment, and forming or casting of the melted product. The energy requirement for melting is the primary factor influencing the cost of ex situ vitrification. Different sources of energy can be used for this purpose, depending on local energy costs. Process heat losses and water content of the feed should be controlled in order to minimize energy requirements. Vitrified material with certain characteristics may be obtained by using additives such as sand, clay and/or native soil. The vitrified waste may be recycled and used as clean fill, aggregate, or other reusable materials (Smith et al., 1995).

In situ vitrification (ISV) involves passing electric current through the soil using an array of electrodes inserted vertically into the contaminated region. Each setting of four electrodes is referred to as a melt. If the soil is too dry, it may not provide sufficient conductance and a trench containing flaked graphite and glass frit (ground glass particles) must be placed between the electrodes to provide an initial flow path for the current. Resistance heating in the starter path melts the soil. The melt grows outward and down as the molten soil usually provides additional conductance for the current. A single melt can treat up to 1000 tons of contaminated soil to depths of 6 m, at a typical treatment rate of 3 to 6 tons per hour.

Larger areas are treated by fusing together multiple individual vitrification zones. The main requirement for in situ vitrification is the ability of the soil melt to carry current and solidify as it cools. If the alkali content (as Na_2O and K_2O) of the soil is too high (1.4 wt%) the molten soil may not provide enough conductance to carry the current (Buelt and Thompson, 1992).

Toxicity and/or Mobility Reduction

Chemical and/or biological processes can be used to alter the form of metal contaminants in order to decrease their toxicity and/or mobility.

A) Chemical Treatment

Chemical reactions can be initiated that are designed to decrease the toxicity or mobility of metal contaminants. The three types of reactions that can be used for this purpose are oxidation, reduction, and neutralization reactions. Chemical oxidation changes the oxidation state of the metal atom through the loss of electrons. Commercial oxidizing agents are available for chemical treatment, including potassium permanganate, hydrogen peroxide, hypochlorite and chlorine gas. Reduction reactions change the oxidation state of metals by adding electrons. Commercially available reduction reagents include alkali metals (Na, K), sulfur dioxide, sulfite salts, and ferrous sulfate. Changing the oxidation state of metals by oxidation or reduction can detoxify, precipitate, or solubilize the metals (NRC, 1994).

Chemical neutralization is used to adjust the pH balance of extremely acidic or basic soils and/or groundwater. This procedure can be used to precipitate insoluble metal salts from contaminated water, or in preparation for chemical oxidation or reduction.

Chemical treatment can be performed ex situ or in situ. However in situ chemical agents must be carefully selected so that they do not further contaminate the treatment area. The primary problem associated with chemical treatment is the nonspecific nature of the chemical reagents. Oxidizing/reducing agents added to the matrix to treat one metal will also target other reactive metals and can make them more toxic or mobile (NRC, 1994). Also, the long-term stability of reaction products is of concern since changes in soil and water chemistry might reverse the selected reactions.

Chemical treatment is often used as pretreatment for S/S and other treatment technologies. Reduction of Cr(VI) to Cr(III) is the most common form of chemical treatment and is necessary for remediation of wastes containing Cr(VI) by precipitation or S/S. Chromium in its Cr(III) form is readily precipitated by hydroxide over a wide range of pH values. Acidification may also be used to aid in Cr(VI) reduction. Arsenic may be treatable by chemical oxidation since arsenate, As(V), is less toxic, soluble and mobile than arsenite, As(III). Bench-scale work has indicated that arsenic stabilization may be achieved by precipitation and coprecipitation with Fe(III) (Smith et al., 1995).

B) Permeable Treatment Walls

Treatment walls remove contaminants from groundwater by degrading, transforming, precipitating or adsorbing the target solutes as the water flows through permeable trenches containing reactive material within the subsurface (Vidic and Pohland, 1996). Several methods are available for installation of permeable treatment walls, some of which employ slurry wall construction technology to create a permeable reactive curtain. The reactive zone can use physical, chemical and biological processes, or a combination of these. The ground-water flow through the wall may be enhanced by inducing a hydraulic gradient in the direction of the treatment zone or channeling ground-water flow toward the treatment zone (NRC, 1994).

Several types of treatment walls are being tried for arresting transport of metals in groundwater at contaminated sites. Trench materials being investigated include zeolite, hydroxyapatite, elemental iron, and limestone (Vidic and Pohland, 1996). Applications of elemental iron for chromium (VI) reduction and limestone for lead precipitation and adsorption are described below.

C) Elemental Iron

Trenches filled with elemental iron have shown promise for remediation of metalscontaminated sites. While investigations of this technology have focused largely on treatment of halogenated organic compounds, studies are being performed to assess the applicability to remediation of inorganic contaminants (Powell et al., 1994).

Low oxidation-state chemical species can serve as electron donors for the reduction of higher oxidation-state contaminants. This ability can be exploited to remediate metals that are more toxic and mobile in higher oxidation states, such as Cr(VI). Results of column experiments performed by Powell et al. (1994) and batch experiments performed by Cantrell et al. (1995) showed that chromate reduction was enhanced in systems containing iron filings in addition to the natural aquifer material. A field experiment has been initiated by researchers at the U.S. EPA National Risk Management Research Laboratory to investigate the use of zero-valent iron for chromium remediation at the U.S. Coast Guard air support base near Elizabeth City, North Carolina. Preliminary results indicate that the test barrier has reduced chromate in the groundwater to below detection limits (Wilson, 1995).

D) Limestone Barriers

The use of limestone treatment walls has been proposed for sites with metals contamination, in particular former lead acid battery recycling sites which have lead and acid contamination in groundwater and soil. In such cases, a limestone trench can provide neutralization of acidic groundwater. The attendant rise in pH promotes immobilization of any dissolved lead through precipitation and/or adsorption onto minerals. A limestone trench system is in design for implementation at the Tonolli Superfund site in Nesquehoning, Pennsylvania (U.S. EPA, 1992b).

There is some experience in the coal mining industry with use of limestone in the manner anticipated for the Tonolli site. Most of this experience has been acquired since 1990, when the concept of “anoxic limestone drains” was introduced (Turner and McCoy, 1990). Since that time, numerous limestone drain systems have been installed at Appalachian coal field sites (primarily in Kentucky, West Virginia, and Pennsylvania) in an attempt to control acid mine drainage. Summaries of installations and evolving design considerations are provided in Hedin and Nairn (1992), Hedin et al. (1994), and Hedin and Watzlaf (1994).

Design and operating guidelines for the anoxic limestone drains have for the most part been developed from trial and observation. Briefly, the systems in use employ fairly large, #3 or #4 (baseball size) limestone rocks. Anoxic mine water is directed to the limestone drain, which is installed with a soil cover to inhibit contact with air. Hedin and Nairn (1992) report that “some systems constructed with limestone powder and gravel have failed, apparently because of plugging problems.” Preliminary review of the literature on design of anoxic limestone drains indicates primary concern with maintenance of anoxic conditions in the drains. If high dissolved concentrations of Fe are present and aerobic conditions develop, insoluble ferric hydroxide can form and coat the limestone, rendering it ineffective. High concentrations of aluminum are also a concern, as aluminum hydroxide can precipitate and yield the same kind of coating problems. With use of large diameter stones, plugging is prevented even if precipitation occurs and the stones become coated with precipitate. Available operating data for anoxic limestone drains indicate that they can be effective in raising the pH of strongly acidic water. Hedin and Watzlaf (1994) reviewed operating data for 21 limestone drain systems. The data they compiled showed fairly consistent increases in pH of highly acidic mine drainage (at pH 2.3 to 3.5) to pH values in the range of 6.0 to 6.7.

Thus, there is clearly precedent for employing the limestone drain approach with some confidence of success in raising pH of highly acidic water. Long term (i.e., greater than 10 years) performance cannot be predicted with confidence as there has been relatively short duration operating experience. However, experience to date indicates clearly that limestone drain systems can operate effectively under appropriate conditions, especially anoxic or low-oxygen groundwater, for at least several years.

E) Biological Treatment

Biological treatment technologies are available for remediation of metals-contaminated sites. These technologies are commonly used for the remediation of organic contaminants and are beginning to be applied for metal remediation, although most applications to date have been at the bench and pilot scale (Schnoor, 1997). Biological treatment exploits natural biological processes that allow certain plants and microorganisms to aid in the remediation of metals. These processes occur through a variety of mechanisms, including adsorption, oxidation and reduction reactions, and methylation (Means and Hinchee, 1994).

F) Bioaccumulation

Bioaccumulation involves the uptake of metals from contaminated media by living organisms or dead, inactive biomass. Active plants and microorganisms accumulate metals as the result of normal metabolic processes via ion exchange at the cell walls, complexation reactions at the cell walls, or intra- and extracellular precipitation and complexation reactions.

Adsorption to ionic groups on the cell surface is the primary mechanism for metal adsorption by inactive biomass. Accumulation in biomass has been shown to be as effective as some ion exchange resins for metals removal from water (Means and Hinchee, 1994).

G) Phytoremediation

Phytoremediation refers to the specific ability of plants to aid in metal remediation. Some plants have developed the ability to remove ions selectively from the soil to regulate the uptake and distribution of metals. Most metal uptake occurs in the root system, usually via absorption, where many mechanisms are available to prevent metal toxicity due to high concentration of metals in the soil and water. Potentially useful phytoremediation technologies for remediation of metals-contaminated sites include phytoextraction, phytostabilization and rhizofiltration (U.S. EPA, 1996b).

H) Phytoextraction

Phytoextraction employs hyperaccumulating plants to remove metals from the soil by absorption into the roots and shoots of the plant. A hyperaccumulator is defined as a plant with the ability to yield 0.1% chromium, cobalt, copper or nickel or 1% zinc, manganese in the aboveground shoots on a dry weight basis. The aboveground shoots can be harvested to remove metals from the site and subsequently disposed as hazardous waste or treated for the recovery of the metals.

I) Phytostabilization

Phytostabilization involves the use of plants to limit the mobility and bioavailability of metals in soil. Phytostabilizers are characterized by high tolerance of metals in surrounding soils but low accumulation of metals in the plant. This technique may be used as an interim containment strategy until other remediation techniques can be developed, or as treatment at sites where other methods would not be economically feasible.

J) Rhizofiltration

Rhizofiltration removes metals from contaminated groundwater via absorption, concentration and precipitation by plant roots. This technique is use to treat contaminated water rather than soil and is most effective for large volumes of water with low levels of metal contamination. Terrestrial plants are more effective than aquatic plants because they develop a longer, more fibrous root system that provides a larger surface area for interaction. Wetlands construction is a form of rhizofiltration that has been demonstrated as a costeffective treatment for metals-contaminated wastewater.

K) Bioleaching

Bioleaching uses microorganisms to solubilize metal contaminants either by direct action of the bacteria, as a result of interactions with metabolic products, or both. Bioleaching can be used in situ or ex situ to aid the removal of metals from soils. This process is being adapted from the mining industry for use in metals remediation. The mechanisms responsible for bioleaching are not fully defined, but in the case of mercury bioreduction (to elemental mercury) is thought to be responsible for mobilization of mercury salts (Means and Hinchee, 1994).

L) Biochemical Processes

Microbially mediated oxidation and reduction reactions can be manipulated for metal remediation. Some microorganisms can oxidize/reduce metal contaminants directly while others produce chemical oxidizing/reducing agents that interact with the metals to effect a change in oxidation state. Mercury and cadmium have been observed to be oxidized through microbial processes, and arsenic and iron are readily reduced in the presence of appropriate microorganisms. The mobility of metal contaminants is influenced by their oxidation state. Redox reactions can therefore be used to increase or decrease metal mobility (Means and Hinchee, 1994).

Methylation involves attaching methyl groups to inorganic forms of metal ions to form organometallic compounds. Methylation reactions can be microbially mediated. Organometallic compounds are more volatile than inorganic metals and this process can be used to remove metals through volatilization and subsequent removal from the gas stream. However, organometallics are also more toxic and mobile than other metal forms and may potentially contaminate surrounding surface waters and groundwater (Means and Hinchee, 1994).

Physical Separation

Physical separation is an ex situ process that attempts to separate the contaminated material from the rest of the soil matrix by exploiting certain characteristics of the metal and soil. Physical separation techniques are available that operate based on particle size, particle density, surface and magnetic properties of the contaminated soil. These techniques are most effective when the metal is either in the form of discrete particles in the soil or if the metal is sorbed to soil particles that occur in a particular size fraction of the soil. Physical separation is often used as a form of pretreatment in order to reduce the amount of material requiring subsequent treatment (Rosetti, 1993). Several techniques are available for physical separation of contaminated soils including screening, classification, gravity concentration, magnetic separation and froth flotation.

Screening separates soils according to particle size by passing the matrix through a sieve with particular size openings. Smaller particles pass through the sieve and leave larger particles behind, however, the separation is not always complete. Screening may be performed as a stationary process or with motion using a wet or dry process stream (Smith et al., 1995).

Classification involves separation of particles based upon the velocity with which they fall through water (hydroclassification) or air (air classification). Hydroclassification is more common for soil separation and may be performed using a non-mechanical, mechanical or a hydraulic classifier (Rosetti, 1993).

Gravity concentration relies on gravity and one or more other forces (centrifugal force, velocity gradients, etc.) that may be applied to separate particles on the basis of density differences. Gravity concentration may be achieved through the use of a hydrocyclone, jig, spiral concentrator, or shaking table (Rosetti, 1993).

Froth flotation uses air flotation columns or cells to remove particles from water. In this process, air is sparged from the bottom of a tank or column that contains a slurry of the contaminated material. Some metals and minerals attach to the air bubbles due to particular surface properties, such as hydrophobicity. Froth flotation can be used to remove metals that attach to air bubbles, or to remove other minerals while the metal remains in the slurry (Rosetti, 1993).

Magnetic separation subjects particles to a strong magnetic field using electromagnets or magnetic filters and relies on differences in magnetic properties of minerals for separation. Low intensity wet magnetic separators are the most common magnetic separation devices. This process can recover a wide variety of minerals and is particularly successful for separating ferrous from nonferrous minerals (Allen and Torres, 1991).

Extraction

Metals-contaminated sites can be remediated using techniques designed to extract the contaminated fraction from the rest of the soil, either in situ or ex situ. Metal extraction can achieved by contacting the contaminated soil with a solution containing extracting agents (soil washing and in situ soil flushing) or by electrokinetic processes. The contaminated fraction of soil and/or process water is separated from the remaining soil and disposed or treated.

Soil Washing

Soil washing can be used to remove metals from the soil by chemical or physical treatment methods in aqueous suspension. Soil washing is an ex situ process that requires soil excavation prior to treatment. Chemical treatment involves addition of extraction agents that react with the contaminant and leach it from the soil (Elliot and Brown, 1989; Ellis and Fogg, 1985; Tuin and Tels, 1990). The liquid containing the contaminants is separated from the soil resulting in a clean solid phase. Physical treatment is achieved by particle size separation technologies adapted from mineral processing to concentrate the contaminant in a particular size fraction (Allen and Torres, 1991).

Fine particles (<63 :m) often contain the majority of contaminated material because they bind contaminants strongly due to their large and reactive surface area. Many current soil washing approaches attempt to separate the fine fraction from the remainder of the soil in order to reduce the amount of material for subsequent treatment or disposal (Rosetti, 1993).

Particle size separation techniques may not be successful if fine particle, e.g., metal oxide, coatings are present on particles in larger size fractions (Van Ben Schoten et al., 1994).

Preliminary Screening

After excavation, the soil undergoes preliminary screening and preparation in order to separate large rocks and debris from the contaminated matrix. Residual fines may be adhered to the surface of large rocks and are often washed off prior to return of the large rocks to the site (Rosetti, 1993).

Secondary Screening

Most soil washing processes employ secondary screening to segregate the particles into different size fractions, usually between 5 mm and 60 mm. Most secondary screening processes involve making an aqueous slurry of the soil stream and wet screening/sieving of the slurry. The particles in this size range are considered less contaminated than the finer fraction and may be returned to the site as clean soil after separation from the water (Rosetti, 1993).

Chemical Treatment

Chemical treatment may be used to solubilize contaminants from the most contaminated fraction of the soil. Chemical treatment is performed in an aqueous slurry of the contaminated material to which an extracting agent is added. The extraction is performed in a mixing vessel or in combination with the physical treatment stage. The type of extractant used will depend on the contaminants present and the characteristics of the soil matrix. Many processes manipulate the acid/base chemistry of the slurry to leach contaminants from the soil (Tuin and Tels, 1990). However, if a very low pH is required concerns about dissolution of the soil matrix may arise. Chelating agents (e.g., EDTA) selectively bind with some

metals and may be used to solubilize contaminants from the soil matrix (Elliot and Brown, 1989). Oxidizing and reducing agents (e.g., hydrogen peroxide, sodium borohydride) provide yet another option to aid in solubilization of metals since chemical oxidation/ reduction can convert metals to more soluble forms (Assink and Rulkens, 1989; Tuin et al., 1987). Finally, surfactants may be used in extraction of metals from soil (U.S. EPA, 1996b).

Physical Treatment

Physical treatment is used to separate the contaminated fraction, usually the fine materials, from the rest of the soil matrix. Physical separation may be performed alone or in conjunction with chemical treatment, as in most soil washing processes. The most common method for physical separation in soil washing uses rotary attrition scrubbers to isolate the contaminated particles. The rotation of the slurry causes contact between large particles, resulting in attrition of the larger particles which releases the contaminant and contaminated fines to the slurry. The contaminant remains suspended in solution or sorbs to the reactive fine particles. Vibration units are also available to perform similar separations (Rosetti, 1993).

Hydrocyclones are the most common method used to separate fines from the clean soil. Other options are available for fine particle separation, including mechanical classifiers, gravity classifiers, spiral concentrators, and magnetic separators (Rosetti, 1993). Froth flotation can be used to combine physical and chemical treatment processes into one step. For this method, extracting agent is added to the soil before it enters the froth flotation cell. The slurry is leached in the tanks to remove the contaminant and the fines (<50 :m) are then separated from coarse particles in the flotation unit (Rosetti, 1993).

A) Dewatering

After the contaminated fine particles are separated from the clean coarse particles, both fractions are dewatered. The fine fraction is usually dewatered using a belt filter or filter press and disposed of in a landfill. Larger particles are rinsed to remove residual extracting solution and contaminant and dewatered using belt and filter presses. This fraction is considered clean and can be returned to the site.

B) Water Treatment

The contaminated water from rinsing and dewatering steps is treated by manipulating the solution chemistry to separate the contaminant from the extractant if possible. Contaminants can then be removed from solution, most commonly by precipitation or sedimentation, and are dewatered before disposal with the contaminated fines. The extracting agent and process water can be recycled for reuse.

C) Pyrometallurgical Extraction

Pyrometallurgical technologies use elevated temperature extraction and processing for removal of metals from contaminated soils. Soils are treated in a high-temperature furnace to remove volatile metals from the solid phase. Subsequent treatment steps may include metal recovery or immobilization. Pyrometallurgical treatment requires a uniform feed material for efficient heat transfer between the gas and solid phases and minimization of particulates in the off-gas. This process is usually preceded by physical treatment to provide optimum particle size. Pyrometallurgical processes usually produce a metal-bearing waste slag, but the metals can also be recovered for reuse (U.S. EPA, 1996c).

D) In Situ Soil Flushing

In situ soil flushing is used to mobilize metals by leaching contaminants from soils so that they can be extracted without excavating the contaminated materials. An aqueous extracting solution is injected into or sprayed onto the contaminated area to mobilize the contaminants usually by solubilization. The extractant can be applied by surface flooding, sprinklers, leach fields, vertical or horizontal injection wells, basin infiltration systems or trench infiltration systems (U.S. EPA, 1996b). After being contacted with the contaminated material the extractant solution is collected using pump-and-treat methods for disposal or treatment and reuse. Similar extracting agents are used for in situ soil flushing and soil washing, including acids/bases, chelating agents, oxidizing/ reducing agents and surfactants/ cosolvents. Also, water can be used alone to remove water-soluble contaminants such as hexavalent chromium. The applicability of in situ soil flushing technologies to contaminated sites will depend largely on site-specific properties, such as hydraulic conductivity, that influence the ability to contact the extractant with contaminants and to effectively recover the flushing solution with collection wells (NRC,1994).

E) Electrokinetic Treatment

Electrokinetic remediation technologies apply a low density current to contaminated soil in order to mobilize contaminants in the form of charged species. The current is applied by inserting electrodes into the subsurface and relying on the natural conductivity of the soil (due to water and salts) to effect movement of water, ions and particulates through the soil.

Water and/or chemical solutions can also be added to enhance the recovery of metals by this process. Positively charged metal ions migrate to the negatively charged electrode, while metal anions migrate to the positively charged electrode. Electrokinetic treatment concentrates contaminants in the solution around the electrodes. The contaminants are removed from this solution by a variety of processes, including electroplating at the electrodes, precipitation/coprecipitation at the electrodes, complexation with ion exchange resins, or by pumping the water from the subsurface and treating it to recover the extracted metals (Smith et al, 1995).

Electrokinetic treatment is most applicable to saturated soils with low ground-water flow rates and moderate to low permeability. The efficiency of metal removal by this process will be influenced by the type and concentration of contaminant, the type of soil, soil structure, and interfacial chemistry of the soil.

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Chapter

8

Combating Climate Change by Restoration of Degraded Land

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Chapter 8

Combating Climate Change by Restoration of Degraded Land

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1 Restoration of degraded land in the context of climate change: definitions and historical evolution

Source: Mansourian, S., (2005) Overview of Forest Restoration Strategies and Terms. In Mansourian, S., Vallauri, D., Dudley, N., Forest Restoration in Landscapes - Beyond Planting Trees, pp. 8-17, Springer.

1.1 Introduction

When forests are lost or degraded, we lose far more than just the trees that they contain. Forests provide a large number of goods and services, including habitat for species, homeland for indigenous peoples, recreational areas, food, medicines, and environmental services such as soil stabilisation. And as forest areas are reduced, pressure on remaining forests increases.

Efforts at reversing this trend have had only limited success. For many, restoration signifies large-scale afforestation or reforestation (mainly using fast growing exotic species), which have only limited conservation benefits. This has been the approach taken by many governments that are seeking to support a timber industry or create jobs or, equally, those who have taken a simplistic approach to flood or other disaster mitigation. On the other hand, some have sought to re-create original forests, a near-impossible feat in areas where millennia of human intervention have modified the landscape and local conditions.

Many different terms are used to describe these different approaches and can result in some confusion or misconceptions. We attempt here to cover most of the terminology used in English taken from the Society for Ecological Restoration International (SERI), which has made the best attempt at cataloguing and defining these different terminologies and concepts. It must be noted that this complexity is also apparent and sometimes exacerbated when translating these terms into other languages.

1.2 Definitions and examples

1.2.1 Ecological Restoration

Ecological restoration is defined as the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed. It is an intentional activity that initiates or accelerates the recovery of an ecosystem with respect to its health, integrity, and sustainability.

Example 1: In 2000, in an attempt to re-create a native wild wood, the Scottish nongovernmental organisation (NGO), Borders Forest Trust, together with many partners, bought a 600-hectare plot of land, Carrifran, in the Southern Uplands of Scotland in order to restore its original forest. Thanks to fossil pollen buried deep in peat, it was possible to identify the nature of the variety of species previously found on this now near-denuded site and therefore to develop a restoration plan that aimed to re-create the species' mix that had occurred in the past. Thousands of native tree seeds from surviving woodland remnants in the vicinity were collected. A total of 103.13 hectares (165,008 trees) have been planted at Carrifran since the start of the project. The upper part of the site is being allowed to regenerate naturally.

1.2.2 Rehabilitation

Rehabilitation emphasises the reparation of ecosystem processes, productivity, and services, whereas the goals of restoration also include the reestablishment of the preexisting biotic integrity in terms of species' composition and community structure.

Example 2: Bamburi Cement's quarries in Mombasa (Kenya) were once woodland expanses covering 1,200 hectares. Starting in 1971, experiments began with the rehabilitation of the disused quarries. In the face of badly damaged soils, three tree species proved capable of withstanding the difficult growing conditions: Casuarina equisetifolia, Conocarpus lancifolius, and the coconut palm. The Casuarina is nitrogen fixing and is drought and salt tolerant, enabling it to colonise areas left virtually without soil. The Conocarpus is also a drought-, flood-, and salt-tolerant swamp tree. The decomposition of the Casuarina leaf litter was initially very slow due to high protein content, thus impeding the nutrient cycling process, although this problem was overcome by introducing a local red-legged millipede that feeds on the dry leaves and starts the decomposition process. Today this area contains more than 200 coastal forest species and a famous nature trail, attracting 100,000 visitors a year since opening in 1984.

1.2.3 Reclamation

Reclamation is a term commonly used in the context of mined lands in North America and the United Kingdom. It has as its main objectives the stabilisation of the terrain, assurance of public safety, aesthetic improvement, and usually a return of the land to what, within the regional context, is considered to be a useful purpose.

Example 3: A large open-cut bauxite mine at Trombetas in Pará state in central Amazonia is located in an area of relatively undisturbed evergreen equatorial moist forest. A reclamation programme has been developed to restore the original forest cover as far as possible. The project has treated about 100 hectares of mined land per year for the last 15 years. First, the mined site was levelled and topsoil replaced to a depth of about 15 cm using topsoil from the site that was removed and stockpiled (for lessthan 6 months) prior to mining. Next, the site was deep-ripped to a depth of 90cm (1-m spacing between rows). Trees were planted along alternate rip lines at 2-m spacings (2500 trees per hectare) using direct seeding, stumped saplings, or potted seedlings. Some 160 local tree species were tested for their suitability in the programme, and more than 70 species from the local natural forests are now routinely used. After 13 years most sites have many more tree and shrub species than those initially planted because of seeds stored in the topsoil or colonisation from the surrounding forest. Not surprisingly, the density of these new colonists is greater at sites near intact forest, but dispersal was evident up to 640 m away from old-growth forest. The new species, most of which have small seed, have been brought to the site by birds, bats, or terrestrial mammals.

1.2.4 Afforestation/Reforestation

Afforestation and reforestation refer to the artificial establishment of trees, in the former case where no trees existed before. In addition, in the context of the U.N.'s Framework Convention on Climate Change (UNFCCC) and the Kyoto protocol, specific definitions have been agreed on reforestation and afforestation.

Afforestation is defined by the UNFCCC as "the direct human-induced conversion of land that has not been forested for a period of at least 50 years to forested land through planting, seeding, and/or human induced promotion of natural seed sources."

Example 4: During the middle years of the 20th century, very large areas of longdeforested land were planted in Scotland by the state forestry body, initially as a strategic resource. In contrast to the Borders Forest Trust project described above, these efforts made no attempt to re-create the original forest, instead using exotic monocultures, mainly of Sitka spruce from Alaska (Picea sitchensis) or Norway spruce (Picea abies) from mainland Europe. Planting was generally so dense that virtually no understorey plant species developed.

Reforestation is defined by the UNFCCC as "the direct human-induced conversion of nonforested land to forested land through planting, seeding, and/or the human-induced promotion of natural seed sources, on land that was forested but that has been converted to nonforested land."

Example 5: In Madagascar, large plantation projects were planned in the early 1970s to supply a paper mill on the "Haut Mangoro." By 1990 about 80,000 hectares had been planted, 97 percent of which was Pinus spp. This project created significant social and political tensions, as the local population systematically opposed a project that it felt was not providing much benefit.

Broad definitions and explanations of what restoration entails can be found in most conservation and forestry institutions. Nonetheless, little of this has reached the field. Because of its complexity, large-scale restoration requires a mixture of responses from practical to political and many practitioners are at a loss as to where to begin.

Some practical guidance is available:

- The Society for Ecological Restoration (SERI) has developed guidelines for restoration (see Guidelines for Developing and Managing Ecological Restoration Projects, 2000, at www.ser.org).
- The International Tropical Timber Organisation (ITTO) developed some guidelines on the restoration, management, and rehabilitation of degraded and secondary tropical forests.
- The International Union of Forest Research Organisations (IUFRO) runs a special programme on correct usage of technical terms in forestry called SilvaVoc, available on its Web site: www.iufro.org/science/special/silvavoc/.
- The Nature Conservancy (TNC)18 has identified some guidance on when and where to restore (see Geography of Hope Update, When and Where to Consider Restoration in Ecoregional Planning at www.conserveonline.org).
- In 2003, IUCN and WWF published a book, by David Lamb and Don Gilmour, 19 Rehabilitation and Restoration of Degraded Forests, which covers site-based techniques to restoration (summarised in a paper in this manual) but also highlights some of the gaps.
- Cambridge Press has produced a Handbook of Ecological Restoration, 20 which is a two-volume handbook containing a large amount of material on the diverse aspects of restoration.

1.3 Evolution

Source: Uriel N. Safriel (2007) The Assessment of Global Trends in Land Degradation. In MannavaV.K. Sivakumar and Ndegwa Ndiang'ui. Climate and Land Degradation, pp 2-36, Springer Berlin Heidelberg New York.

The motivation for quantitative assessment of land degradation at a global scale is its recognition as an environmental issue of global societal implications. Yet, due to the non-robust definition of "land degradation" and to the paucity of field data, the five global assessments carried out and presented between 1977 and 2003 differ in the selection of measurable attributes of land degradation, in the quality of the data sets, and in their spatial coverage. This resulted in a plethora of degradation estimates ranging 15% to 63% of global degradation and 4% to 74% of dryland degradation. Of these, the figure of 70% degradation (for the drylands only, comprising 41% of global land) has been cited more than the others. Though likely to be overly exaggerated (because it stands for a combination of degradation degree of a land unit and its spatial extent within the mapping unit of which it is a part), this high estimate has apparently served well the globality notion of the dryland degradation syndrome, essential to rallying support for international development assistance under the UNCCD. This thirst for development assistance aimed at "combating desertification" attracted to the UNCCD some 70 non-dryland developing countries (compared to 93 developing dryland country Parties) which experience land degradation that is not included in global assessments of desertification, since only dryland degradation qualifies as "desertification". The texts of the various assessments, including that of GLASOD as well as the UNCCD definition often trade off "desertification" with "susceptibility" to or "threat" of desertification. This suggests that an assessment of vulnerability to desertification rather than its actual occurrence are of higher credibility and utility for policy- and decision-making.

Though soil degradation featured highly in the currently available global degradation assessments, remotely-sensed vegetation attributes not only assess the most valued but threatened ecosystem service, but are also amenable for assessment at the global scale. However, caution is required when using this tool especially in drylands where productivity is tightly linked to rainfall variations. The monitoring required to meet the persistence criterion for qualifying desertification can be also used to detect current desertification trends, which are of relevance for policy-making even more than defining current desertification status. To discern changes of productivity due to state of the land from those due to rainfall features, the ratio of NPP to rainfall (RUE) could be useful were it not negatively correlated with rainfall itself. An alternative method for detecting degradation trends, the Residual NPP Trends (RESTREND) is currently under development. It is based on an analysis of the residuals of the productivity-rainfall relationship throughout a time period for each pixel in the explored region. A statistically significant negative regression of the residuals on time identifies a degradation trend, and the slope stands for its magnitude. To be reliable on a global scale such a remote-sensing approach would serve for guiding field observations required for its own verification.

2 Carbon fluxes and the restoration of degraded soil

Source: FAO (2004) Carbon sequestration in dryland soils, 129 pp, (http://www.fao.org/docrep/007/y5738e/y5738e0a.htm#TopOfPage)

2.1 Introduction

Land-use change and soil degradation are major processes for the release of CO_2 to the atmosphere. The increase in greenhouse gases (GHGs) in the atmosphere is now recognized to contribute to climate change (IPCC, 2001). Although uncertainties remain regarding the causes, consequences and extent of climate change, it is believed that human activities are having an impact on the energy balance of the earth. Its influence on the climate is a major concern in the twenty-first century. This concern has led to the 1997 international agreement in Kyoto (the so-called Kyoto Protocol), whereby most countries are committed to reducing their GHG emissions to the atmosphere. In this context, new strategies and policies within the international framework have been developed for the implementation of agriculture and forestry management practices that enhance carbon sequestration (CS) both in biomass and soils. These activities are included in Articles 3.3 and 3.4 of the Kyoto Protocol (KP) and are known as "land use, land-use change and forestry" (LULUCF) (IPCC, 2000).

The importance of these activities is that any action taken to sequester C in biomass and soils will generally increase the organic matter content of soils, which in turn will have a positive impact on environmental, agricultural and biodiversity aspects of ecosystems. The consequences of an increase in soil carbon storage can include increases in soil fertility, land productivity for food production and security, and prevention of land degradation. Therefore, they might constitute win - win situations.

A proper analysis of the impact of climate change must also consider other global concerns such as loss of biodiversity, changes in land use, growing food demand, and soil degradation. International United Nations conventions exist regarding these problems: the Convention on Biological Diversity (CBD), the Convention to Combat Desertification (CCD), the Ramsar Convention of Wetlands, and there are also several related United Nations programmes, e.g. the United Nations Environment Programme (UNEP), and the United Nations Development Programme (UNDP). Other initiatives, such as the Millennium Ecosystem Assessment, funded internationally by the World Bank, the United Nations Global Environment Facility (GEF), etc., aim to determine the state of the earth's ecosystems, trying to take into consideration all global problems and the interactions among them.

2.2 The terrestrial carbon cycle

To help understand the concept of CS, Figure 2.1 presents a simplified diagram of the carbon balance of terrestrial ecosystems. The main entry of C into the biosphere is through the process of photosynthesis or gross primary productivity (GPP), that is the uptake of C from the atmosphere by plants. Part of this C is lost in several processes: through plant respiration (autotrophic respiration); as a result of litter and soil organic matter (SOM) decomposition (heterotrophic respiration) and as a consequence of further losses caused by fires, drought, human activities, etc.

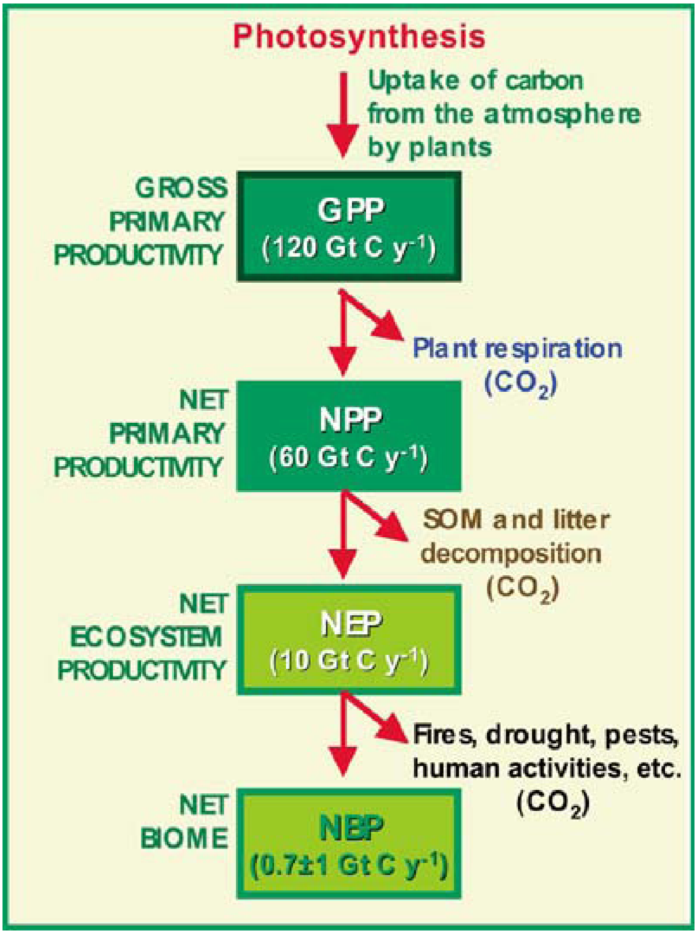

Figure 1 *Terrestrial global carbon balance (simplified)*

2.3 Soil degradation

Soil degradation is a global problem (UNEP, 1992), particularly the desertification of drylands. Most of the drylands are on degraded soils, soils that have lost significant amounts of C. Therefore, the potential for sequestering C through the rehabilitation of drylands is substantial (FAO, 2001). Lal (2000) estimated the magnitude of the potential for sequestering C in soils in terrestrial ecosystems at 50 - 75 percent of the historic carbon loss. Furthermore, Lal hypothesized that annual increase in atmospheric CO_2 concentration could be balanced out by the restoration of 2 000 000 000 ha of degraded lands, to increase their average carbon content by 1.5 tonnes/ha in soils and vegetation. The benefits would be enormous. Enhancing CS in degraded agricultural lands could have direct environmental, economic, and social benefits for local people. Therefore, initiatives that sequester C are welcomed for the improvement in degraded soils, plant productivity and the consequent food safety and alleviation of poverty in dryland regions.

The effects of soil degradation and desertification affect the global C cycle. Land use change leads to a loss in vegetation cover and subsequent loss in organic C in soils and soil quality. The processes of plant productivity, soil degradation and CS are closely linked. A decline in soil quality leads to a reduction in the soil organic C pool, and an increase in the emission of CO_2 to the atmosphere. The decline in soil quality and structure leads to a loss in the capacity to retain water, and therefore in plant productivity.

2.4 Desertification and carbon sequestration

The effects of desertification on soil quality include:

- loss in soil aggregation
- decrease in water infiltration capacity
- reduction in soil water storage · increase in erosion potential
- depletion in SOM, difficulty in seed germination
- disruption of biogeochemical cycles C, N, phosphorous, sulphur alterations in water and energy balance
- loss of soil resilience

All of these effects accentuate the emission of CO_2 to the atmosphere. Lal (2001) estimated the C loss as a result of desertification. Assuming a C loss of 8 - 12 Mg C/ha (Swift et al., 1994) on a land area of 1 020 000 000 ha (UNEP, 1991), the total historic C loss would amount to 8 - 12 Pg C. Similarly, vegetation degradation has led to a C loss of 4 - 6 Mg C/ha on 2 600 000 000 ha, adding up to 10 - 16 Pg C. The total C loss as a consequence of desertification may be 18 - 28 Pg C. Assuming that two-thirds of the C lost (18 - 28 Pg) can be re-sequestered (IPCC, 1996) through soil and vegetation restoration, the potential of C sequestration through desertification control is 12 - 18 Pg C (Lal, 2001). These estimates provide an idea about the loss of C as a result of desertification and the potential for CS through the restoration of soils in drylands.

Opportunities for improved land management as well as increasing CS should be developed in these areas. Agricultural systems contribute to carbon emissions through the use of fossil fuels in farm operations and through practices that result in loss of organic matter in soils. On the other hand, farming systems can offset carbon losses when accumulating organic matter in the soil, or when aboveground woody biomass is increased, which then acts either as a permanent sink or used as an energy source that substitutes fossil fuel. The potential for global benefits, as well as local benefits, to be obtained from increased CS in drylands should be an additional incentive for stronger support for reforestation and agriculture in drylands.

Although drylands have been studied (Heathcote, 1983; Thomas, 1997), the impact of desertification on the global carbon cycle and the potential impact of desertification control on CS in dryland ecosystems have not been widely investigated. There are few case studies, and little information. Consequently, there is little scientific evidence on the impact of desertification on carbon emission to the atmosphere. The aim here is to assess the state of knowledge, and the potential of different measures to increase CS.

3 Carbon fluxes and the restoration of degraded agricultural and forest lands

3.1 Restoration of degraded agricultural land

Source: Wade, M. R., Gurr, G. M., & Wratten, S. D. (2008). Ecological restoration of farmland: progress and prospects. Philosophical Transactions of the Royal Society B: Biological Sciences, 363(1492), 831-847.

The goal of ecological restoration is to shift an ecosystem towards its pre-disturbed state with respect to ecosystem structure, function and composition (Hobbs & Norton 1996). The approach emphasizes the use of quantitative practices for measuring and restoring ecosystem 'health', including its ability to deliver ecosystem services (Costanza et al. 1997). Sustainable agriculture 'refers to the ability of a farm to continue producing indefinitely with a minimum of outside inputs, or put another way, is defined as agriculture that meets the needs of the present generation while conserving resources for the use of future generations. The continuity of production by using minimal inputs and creating few negative effects is emphasized. 'Farmland' primarily refers to the land use comprising temporary or permanent crops and pastures. For the purposes of the review, this also includes non-crop vegetation, such as hedgerows and remnants of native vegetation, and waterways that are situated on farmland, but not plantation timber or farm forestry. Although farmland is often derived from grassland and woodland, these habitat types per se are generally excluded from the review unless the principles involved in the restoration of these habitats are relevant to that of farmland (Hooper et al. 2002; Ryan et al. 2002).

What causes farmland to become degraded and what are the symptoms of farmland in need of ecological restoration? Farmland and its environs are susceptible to inadvertent or deliberate degradation in their physical, chemical and biological condition by a range of farming activities that primarily result in changes to air quality, biological diversity, climate, soil condition and the quality and quantity of water (reviewed by Meyer & Turner 1992; Matson et al. 1997; Stoate et al. 2001; Robinson & Sutherland 2002; Tilman et al. 2002; Benton et al. 2003; Millennium Ecosystem Assessment 2005). Soil erosion results from the loss of vegetation cover due to burning, grazing and cultivation. Changes in the fertility, structure, acidification and salinization of soils are caused by cultivation, drainage, irrigation and tree removal. Pollution of ground water and eutrophication of rivers and lakes results from off-farm movement of silt, pesticides and nutrients, i.e. fertilizers or animal effluent. Flow rate of rivers is affected by the construction of weirs and levée-banks, diversion of overland water flows to on-farm reservoirs and direct removal for irrigation. There are global impacts on atmospheric constituents (principally carbon dioxide, methane and nitrogen dioxide) and climate (chiefly temperature and rainfall) as a result of forest removal, biomass burning, fertilizers and livestock. Finally, land cover changes lead to both habitat loss and fragmentation, which threaten aquatic and terrestrial taxa (Meyer & Turner 1992; Matson et al. 1997; Stoate et al. 2001; Robinson & Sutherland 2002; Tilman et al. 2002).

Symptoms of degraded farmland include algal blooms and pesticide residues in waterways, pest outbreaks, plant disease epidemics such as 'rural dieback' of native Australian eucalypts, which is principally caused by the root rot fungus Phytophthora cinnamomi, and disease epidemics of livestock, such as foot and mouth disease and influenza A virus (H5N1, 'bird flu'). In addition, there is evidence of yield decline, loss of topsoil through water and wind, hedgerows and field margins removed or sprayed with herbicides, and a general reduction in species richness and abundance of plants and animals (Wills 1993; Stoate et al. 2001; Tilman et al. 2002; Millennium Ecosystem Assessment 2005).

Importantly, agricultural practices have both local and landscape-scale impacts that transcend farm boundaries (Meyer & Turner 1992; Benton et al. 2003; Cramer & Hobbs 2005; Tscharntke et al. 2005). Local intensification includes adverse effects such as shortened crop rotation cycles and increasing input of agrochemicals. On a landscape scale, fields have been amalgamated and enlarged, resulting in simplified landscapes with few or no non-crop habitats remaining (Tscharntke et al. 2005). The total annual external (off-farm) costs of agriculture on natural resources (air, soil and water), biodiversity and human health (pathogens and pesticides) have been estimated for the United Kingdom at £1149–3907 million between 1990 and 1996 (Pretty et al. 2000) and £1514 million in 2000 (Pretty et al. 2005), and for the USA at £3256–9678 million in 2002 (Tegtmeier & Duffy 2004). This equates to £208 ha^{-1} of arable land and permanent pasture for the United Kingdom (UK) in 1996 and £17–55 ha^{-1} of arable land in the USA.

To put these costs into perspective with the external benefits provided by agriculture, the pivotal paper by Costanza et al. (1997) calculated the combined economic value of three ecosystem services (biological control, pollination and food production) from worldwide cropland to be USD$128.8 (£73.802) billion per year or USD$92 (£53) per ha. A caveat here is that Costanza et al. (1997) assigned a nil value to the ecosystem service of habitats or refugia for resident and transient taxa because this service 'do(es) not occur or (is) known to be negligible', hence the true value of cropland is likely to be underestimated. Nevertheless, by these calculations, the worldwide ecosystem service benefits from agriculture are estimated to be £53 $ha^{-1} yr^{-1}$, yet the external costs of intensive agriculture in countries like the UK are £208 $ha^{-1} yr^{-1}$. Equally compelling calculations estimated that the economic benefit to world society from biodiversity is USD$2928 billion. This value included the benefits of activities such as biological pest control, ecotourism, pollination and waste disposal (Pimentel et al. 1997). It is evident that more sustainable agricultural practices in conjunction with ecological restoration methods on farmland are necessary to reduce the unacceptably high external costs of agriculture that are borne by the community. In addition, 'ecological engineering' techniques are available to enhance ecosystem services on farmland, including habitat manipulation tactics for beneficial arthropods that are responsible for biological pest control and contribute to biodiversity in general.

Agriculture and biodiversity conservation have been traditionally viewed as incompatible, with agriculture considered a major driver of species loss for many plant and animal taxa, such as bumble-bees (Bombus spp.) and bird species like skylarks (Alauda arvensis L.) since 1945 (Stoate et al. 2001; Robinson & Sutherland 2002). Agriculture represents the dominant land use throughout much of Western Europe and a significant part of European biodiversity is associated with this habitat. Agroecosystems, however, are very hostile to a wide diversity of species owing to the conversion of complex natural ecosystems to simplified managed ones and the intensification of resource use. Firstly, there is a tendency for simplified cropping systems to be applied to increasingly consolidated land areas, leading to the loss of non-crop habitats, such as field margins and hedgerows, together with the decline in traditional mixed arable and livestock farming. As a result, remnant native vegetation has become fragmented into different patches and there are fewer 'nodes' where field corners join. These nodes can be rich 'hotspots' of invertebrate, vertebrate and plant diversity (Keesing & Wratten 1997). Secondly, there is intensification of resource use in the cropping systems themselves, including greater pesticide and fertilizer usage and shorter fallow periods (Stoate et al. 2001; Pywell et al. 2005). However, more recently, there has been an important move beyond conservation efforts to an appreciation of the value of natural, undisturbed remnants and to a better recognition of the role that highly modified landscapes play in maintaining native biodiversity (Tscharntke et al. 2005). As Novacek & Cleland (2001) pointed out 'we are obviously past any point where strategies that focus on preservation of 'pristine' habitats are sufficient for the job. Greater attention must be placed on human-dominated landscapes that surround the less disrupted areas. In this way, agriculture can make important contributions to high-diversity habitats, while also benefiting from ecosystem services provided from different land use types. We know that invertebrate natural enemies of crop pests visit different habitat types before colonizing agricultural fields (Silberbauer et al. 2004) and improved biological pest control and crop pollination may directly increase farmers' income (Östman et al. 2003; Ricketts et al. 2004).

3.2 Restoration of degraded forest land

Source: Biringer, J., and Lara J. Hansen J. L., (2005) Restoring Forest Landscapes in the Face of Climate Change. In Mansourian, S., Vallauri, D., Dudley, N., Forest Restoration in Landscapes - Beyond Planting Trees, pp. 31-41, Springer.

Climate change is arguably the greatest contemporary threat to biodiversity. It is already affecting ecosystems of all kinds and these impacts are expected to become more dramatic as the climate continues to change due to anthropogenic greenhouse gas emissions into the atmosphere, mostly from fossil fuel combustion.

While restoration is made more difficult by climate change, it can conversely be seen as a possible adaptive management approach for enhancing the resilience of ecosystems to these changes.

Climate change will result in added physical and biological stresses to forest ecosystems, including drought, heat, increased evapotranspiration, altered seasonality of hydrology, pests, disease, and competition; the strength and type of effect will depend on the location. Such stresses will compound existing non-climatic threats to forest biodiversity, including overharvesting, invasive species, pollution,and land conversion.

This will result in forest ecosystems changing in composition and location. Therefore, in order to increase the potential for success, it will be necessary to consider these changes when designing restoration projects. On the other hand, restoration projects can also be viewed as a key aspect of enhancing ecosystem resilience to climate change. Human development has resulted in habitat loss, fragmentation, and degradation. A first step in increasing resilience to the effects of climate change is enhancing or protecting the ecosystem's natural ability to respond to stress and change. Research suggests that this is best achieved with "healthy" and intact systems as a starting point, which can draw on their own internal diversity to have natural adaptation or acclimation potential and therefore greater resilience. Any restoration activities that enhance the ecological health of a system can thus be seen as creating or increasing the potential buffering capacity against negative impacts of climate change. It should be mentioned that there are obvious limits to the rate and extent of change that even a robust system can tolerate.

As a result it is only prudent to conduct restoration for enhancing resilience in tandem with efforts to reduce greenhouse gas emissions, the root cause of climate change.

For many with a forestry background, carbon dioxide sequestration might seem a concomitant advantage to restoration projects, which can aid in reduction of atmospheric concentrations of greenhouse gases. While forests do hold carbon, and their loss does release carbon, their long-term capacity to act as a reliable sink in the face of climate change, especially for effective mitigation, is not a foolproof strategy. Where restoration is promoted with a focus on capturing carbon, an analysis of climate change impacts should be integrated into project planning to determine whether there really are net sequestration benefits. Increased incidence of forest fires as a result of warming and drying trends, for example, could outweigh any efforts to reduce carbon emissions. Case studies of successful resilience-building efforts are not yet plentiful, due to relatively recent revelations about the scale and impact that climate change will have on ecosystems. However, the global temperature has risen 0.7°C as atmospheric concentrations have risen and extinctions and large-scale ecosystem changes are expected. A number of forest types are already being negatively impacted, including tropical mountain cloud forests, dry forests, and forests in the boreal zone, and climate-related extinctions are already thought to have occurred, for example amongst amphibians. Along the coasts, the rising sea level is increasing the vulnerability of mangroves. Restoration as a means to ensure healthy ecosystem structure and function will have a large part to play in adapting ecosystems to these broad-scale changes.

Framework for Understanding Intersection of Resilience-Building and Forest Restoration and Protection:

1. Protection: For some forests protection alone will not increase resilience to climate change. Many tropical montane cloud forests provide a case in point. Australia's Wet Tropics World Heritage Area is expected to experience a 50% reduction in habitat with warming of 1 degree Celsius, which will leave amphibians and other cool-adapted species no upland migration options as conditions become warmer and drier.

2. Sequestration via restoration: Many examples exist where the planting of trees stores carbon but is not coordinated with conservation or resilience-raising advantages. Nonnative trees, such as Eucalyptus, are often planted solely for the carbon benefit, though the planting may cause degradation of the landscape, and thus not provide a buffer against climate change.

3. Resilience/adaptation: Restoration is but one of the many types of management options that increase resilience. For example, actions that respond to changing dynamics such as insect infestations and changing fire patterns are aspects of good forestry that will receive special attention with the advent of climate change. Activities that increase the efficiency of resource use will also increase resilience. In Cameroon, mangroves are being aided by increasing the efficiency of wood-burning stoves so that 75 percent less mangrove wood is needed for cooking, thereby increasing the resilience of the system by reducing harvest levels. Such actions decrease degradation of the mangrove and raise the probability that it will be equipped to respond to the effects of climate change.

4. Sequestration and resilience/adaptation: Restoration and resilience go hand in hand when the impacts of climate change are taken into account in project planning. Whether passive or active restoration, activities target those areas that will be more suitable to climate change, and encourage use of species that will be hardier under new climatic conditions (successful seed dispersers, for example).

5. Intersection of protection, sequestration, and resilience/adaptation: Creating buffer zones through restoration can increase the resilience of protected areas to the impacts of climate change while at the same time sequestering carbon. This scenario is similar to the one above, except that restoration is focussed on increasing the resilience of protected areas by expanding boundaries to increase suitable habitat under changing climatic conditions.

6. Protection and adaptation: Protection can lead to increased resilience to the impacts of climate change, where suitable habitat is intact, and the expansion of boundaries is possible to accommodate species' needs with a changing climate. A successful protected area system includes identification and conservation of mature forest stands, functional groups and keystone species, and climate refugia.

4 Mitigating climate change by restoration of degraded lands

Source: Alan J. Franzluebbers and Paul C. Doraiswamy (2007) Carbon sequestration and land degradation. In MannavaV.K. Sivakumar and Ndegwa Ndiang'ui. Climate and Land Degradation, pp 343-356, Springer Berlin Heidelberg New York.

Storing carbon in soil as organic matter is not only a viable strategy to sequester CO_2 from the atmosphere, but is vital for improving the quality of soil. This presentation describes (1) C sequestration concepts and rationale, (2) relevant management approaches to avoid land degradation and foster C sequestration, and (3) a summary of research quantifying soil C sequestration. The three primary greenhouse gases (CO_2, CH_4, and N_2O) derived from agriculture have increased dramatically during the past century. Conservation management practices can be employed to sequester C in soil, counter land degradation, and contribute to economic livelihoods on farms. Trees can accumulate C in perennial biomass of above-ground and below-ground growth, as well as in the deposition of soil organic matter. Minimal disturbance of the soil surface with conservation tillage is critical in avoiding soil organic C loss from erosion and microbial decomposition. Animal manures contain 40-60% C, and therefore, application to land promotes soil organic C sequestration and provides readily-available, recycled nutrients to crops. Green manures can be used to build soil fertility, often with leguminous plant species having symbiotic root associations with nitrogen-fixing bacteria. Grasslands have great potential to sequester soil organic C when managed properly, but can also be degraded due to overgrazing, careless management, and drought leading to accelerated soil erosion and undesirable species composition. Opportunities exist to capture and retain greater quantity of C from crop and grazing systems when the two systems are integrated. Fertilization is needed to achieve production goals, but when applied excessively it can lead to environmental pollution, especially when considering the energy and C cost of manufacture and transport. Agricultural conservation management strategies to sequester CO_2 from the atmosphere into soil organic matter will also likely restore degraded land and/or avoid further land degradation.

4.1 Introduction

Land degradation is an insidious process that threatens the sustainability of agriculture, not only in the arid and semi-arid regions, but also in the sub-humid and humid regions, as a result of the loss of agro-ecosystem capacity to meet its full potential. Resulting from complex, and little understood, interactions among periodic weather stresses, extreme climatic events, and management decisions, land degradation is a serious global concern in a world searching for sustainable development to meet the needs of a rapidly increasing human population, to reverse the negative impacts of our choices on the environment in which we live, and to fairly distribute the world's resources in a socially justifiable manner.

Atmospheric concentration of radiatively active trace gases [also called greenhouse gases (GHGs)] has been increasing dramatically during the past several centuries (IPCC 2001). Several of the important GHGs in the atmosphere are derived, at least partially, from agricultural activities. Three of the most important GHGs related to agricultural activities are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Carbon dioxide accounts for almost 75% of the global warming potential of GHGs. The source of this CO_2 is dominantly from fossil fuel combustion. Since 1750, the concentration of CO_2 has increased 31%, the concentration of CH_4 has increased 151%, and the concentration of N_2O has increased 17%. In the USA, the contribution of agriculture to GHG emission has been estimated to be only 7% of the country's total GHG emission.

Global concern for the rising atmospheric concentration of GHGs is also increasing, because of the important implications of these gases on global warming. Potentially dramatic consequences of even relatively minor climate change could cause devastating weather-related occurrences, such as increased frequency and duration of droughts, more widespread and severe flooding events, greater frequency and intensity of tornadoes and cyclones, and melting of polar ice caps that could threaten abundant human civilizations along coastal continental areas.

Understanding the linkages between agricultural land-use activities and GHG dynamics should help society to strengthen its resolve to avoid these potentially devastating impacts and design effective mitigation strategies to bolster ecosystem functioning and overcome human-induced land degradation.

Rising concentration of atmospheric CO_2 has been largely attributed to expanding use of fossil fuels as an energy source. Reducing net GHG emission is possible by:

- Reducing fossil fuel combustion and becoming more energy efficient
- Relying more on low-C energy sources, such as
  - Capturing solar energy
  - Generating wind power
  - Harvesting biofuels
- Sequestering C

Carbon sequestration can be defined as the long-term storage of C so that the accumulation of CO_2 in the atmosphere can be reduced or slowed. Carbon sequestration can occur globally in one of several compartments:

- Terrestrial biosphere
- Underground in geologic formations
- Oceans

This focuses on the terrestrial biosphere, which is directly manipulated by agriculture through changes in vegetation and soil disturbance. Carbon sequestration in the terrestrial biosphere can be accomplished by:

- Increasing the net fixation of atmospheric CO_2 by terrestrial vegetation with emphasis on enhancing physiology and rate of photosynthesis of vascular plants.
- Retaining C in plant materials and enhancing the transformation of C to soil organic matter.
- Reducing the emission of CO_2 from soils caused by heterotrophic oxidation of soil organic C.
- Increasing the capacity of deserts and degraded lands to sequester C.

Storing C in soil as organic matter is not only a viable strategy to sequester C from the atmosphere, but is also essential in improving the quality of soil. Soil organic matter plays a vital role in:

- Soil fertility, by slowly supplying nitrogen and many other essential elements and molecules to plants through mineralization/immobilization turnover.
- Water cycling, by contributing to soil aggregation and water-holding capacity.
- Soil biodiversity, by providing the C and energy sources needed for soil biological community development.
- Environmental detoxification, by supplying chemical bonds, physical support, and biological activity.
- Biogeochemical cycling, by storing and delivering many globally important elements interacting through the atmosphere, hydrosphere, lithosphere, and biosphere.

4.2 Management Approaches

The terrestrial C cycle can be simply divided into the two primary processes of photosynthetic uptake of CO_2 from the atmosphere (i.e., C input) and respiration of CO_2 from living organisms back to the atmosphere (i.e., C output). On a global scale under steady-state conditions, rates of C input and output have often been considered balanced (Schlesinger 1997). Terrestrial C sequestration efforts, therefore, must recognize the inherent balance between these processes.

Maximizing C input to the terrestrial biosphere from the atmosphere is possible in agricultural systems through a variety of management options, including:

- *Plant selection*, whereby large differences in photosynthetic capacity occur among species, cultivars, and varieties. Perennial plant species often have advantages over annual crops at capturing C, because of a longer growing season and more extensive root distribution (Liebig et al. 2005). However, selection of appropriate annual crops in rotation sequence can maximize growth potential under certain environments. A continuing effort has focused on cultivating high-biomass producing energy crops to maximize photosynthetic capture of CO_2 (Baral and Guha 2004).
- *Tillage management*, whereby the type and frequency of tillage is used to promote the most prolific plant production possible. Tillage is often used to improve the physical condition of soil so that crops can achieve maximum growth potential, but it is also a tool that disturbs soil and promotes oxidation of soil organic matter (Franzluebbers 2004).
- *Fertilization management*, whereby the source, rate, timing, and placement of fertilizer is used to optimize plant production potential. Sufficiently balanced and adequate nutrient supply are essential management considerations to maximize genetic potential of plants (Lal and Bruce 1999), but the high energy cost of mining and manufacturing inorganic sources of nutrients must be recognized as a source of GHG emission (Schlesinger 2000).
- *Integrated management*, whereby pests can be adequately controlled and environmental and socio-economic consequences of agricultural activities can be balanced with agronomic production considerations (Makumba et al. 2007).

Minimizing C loss from soil to the atmosphere has also been a major focus of agricultural research on C sequestration. Management options to minimize C loss from soil include:

- *Reducing soil disturbance* by less intensive tillage and erosion control (Lal et al. 1998).
- *More fully utilizing available soil water*, which not only promotes optimum plant growth, but also reduces the oxidative capacity of soil microorganisms to decompose soil organic matter and crop residues (Lal 2004).
- *Maintaining surface residue cover* to increase plant water use and production. Surface residue cover also fosters greater fungal abundance in the soil microbial community, which promotes greater stabilization of soil aggregates and resistance of soil organic C to decomposition (Nichols and Wright 2004).

In agriculture, there are many management practices that can be employed to sequester C and counter land degradation. The following sections describe some key management practices to combat land degradation. How these management practices might also contribute to soil C sequestration will be highlighted.

4.2.1 Tree Plantings

Trees can accumulate C in perennial biomass of above-ground and below-ground growth, as well as in the deposition of soil organic matter. The intentional mixing of trees or other woody perennials with agricultural crops, pastures, and/or livestock is defined as agroforestry. Agroforestry exploits the ecological and economic interactions of the different components to attain greater sustainability (Nair 1993). This section focuses on agroforestry-related changes in C accumulation rather than on natural or planted forests.

Issues of importance in agroforestry systems are:

- Climate
- Selecting adapted species
- Soil conditions
- Plant density
- Intended use

- Spatial arrangement of trees and other land uses.

The types of agroforestry practices include complex agroforestry systems, boundary plantings, hedgerow intercropping, and improved fallow (Albrecht and Kandji 2003). Carbon sequestration potential of tropical agroforestry systems has been estimated.

From plantation survey data in Australia (400-600 mm zone), mean C accumulation rate of 3.8 Mg ha^{-1} yr^{-1} occurred in the woody biomass from a variety of tree species. In the central Philippines, C sequestration in the above-ground biomass of Leucaena leucocephala during 6 years of growth was estimated at 10.7 Mg C ha^{-1} yr^{-1} (Lasco and Suson 1999).

Carbon accumulation in the soil is the major sink for hedgerow intercropping systems used to produce biomass for improving soil fertility. In Nigeria, L. Leucocephala and Gliricidia sepium intercropping systems sequestered 0.20 Mg C ha^{-1} yr^{-1} in the topsoil compared with sole cropping (Kang et al 1999). From two experiments in Malawi (6 to 9-year studies), a G. sepium intercropping system sequestered soil organic C at a rate of 1.2 Mg ha^{-1} yr^{-1} in the surface soil (0-20 cm), but at a rate of 6.2 to 11.7 Mg ha^{-1} yr^{-1} when calculated to a depth of 0-200 cm (Makumba et al. 2007). Deep rooting of the trees was considered a key feature of this difference in estimates. Using Century and RothC models in Sudan and Nigeria, soil organic C accumulation with tree plantings was estimated at 0.10 ± 0.05 Mg ha^{-1} yr^{-1} (Farage et al. 2007).

4.2.2 Conservation-Tillage Cropping

Minimal disturbance of the soil surface is critical in avoiding soil organic matter loss from erosion and microbial decomposition. Successful conservation-tillage cropping systems have been developed and evaluated throughout the world. As part of a system for conservation agriculture, conservation-tillage cropping can improve plant production, reduce environmental pollution, and store a greater quantity of soil organic C.

Climatic conditions can influence the amount of soil organic C expected to be sequestered with adoption of conservation tillage. With more extreme dry and/or wet conditions, soil organic C sequestration tended to be highest in milder and warm-wet climatic regions of North America. Mean soil organic C sequestration in North America is estimated at 0.33 Mg C ha^{-1} yr^{-1}. In the warm-moist climatic region of the southeastern USA, adding a cover crop to a conservation-tillage system can nearly double the rate of soil organic C sequestration due to additional plant biomass input and better crop growth due to surface residues (Franzluebbers 2005).

Maintaining adequate surface residue cover with conservation-tillage cropping systems has also been shown to be very important for efficiently utilizing rainfall and producing adequate crop yield. From the 12th year of an irrigated wheat–maize rotation in the volcanic highlands of central Mexico, the rate of water infiltration was 18 cm h^{-1} when crop residue was removed and 90 cm h^{-1} when crop residue was retained on the soil surface with no tillage management (Govaerts et al. 2007). The change in water delivery to the soil resulted in rather dramatic changes in crop yield during the last 7 years of the study, in which maize and wheat yields were 40% greater when crop residue was retained as compared to removal of crop residues.

Table 1 Predicted change in soil erosion and organic C sequestration by EPIC-Century modeling during a 25-year period in Mali (Doraiswamy et al. 2007). Traditional cropping and mean crop yield from 1985-2000 included maize (1.5 Mg ha^{-1}), cotton (1.2 Mg ha^{-1}), and millet and sorghum (1.0 Mg ha^{-1})

Management	Erosion (Mg ha^{-1} yr^{-1})	Change in organic C (Mg C ha^{-1} yr^{-1})
Conventional tillage (CT)	16.5	−0.023
CT with increased fertilizer	15.0	−0.006
Ridge tillage (RT)	6.6	0.001
RT with increased fertilizer	5.9	0.027
RT with fertilizer and residues	3.5	0.086

Fertilizer inputs averaged 24 kg N ha^{-1} and 7 kg P ha^{-1} with the low level and 39 kg N ha^{-1} and 9 kg P ha^{-1} with increased fertilizer level

Using a remote sensing–crop modeling approach in Mali, Doraiswamy et al. (2007) observed that modification of traditional cropping systems to better control erosion with ridge tillage could shift agricultural production in the region from a net emitter of CO_2 to a net sink for CO_2. Combining ridge tillage with other improvements in crop management could reduce soil erosion to 20-40% of that predicted in traditional cropping systems with conventional tillage (table 4.1).

4.2.3 Animal Manure Application

Since animal manure contains 40-60% C, its application to land should promote soil organic C sequestration. In a review of studies conducted in the southeastern USA, poultry litter application to crop and pasture lands led to significant change in soil organic C only when evaluations were conducted for more than 2 years. Conversion of C in poultry litter to soil organic C was 17 + 15% among these studies. Although soil organic C has been shown to increase with animal manure application, very few whole-system data have been collected. Manure application may simply transfer C from one land to another, while investing energy in transport and handling operations. A full C accounting approach is needed to adequately assess manure application as a viable C sequestration strategy.

Other long-term studies on farmyard (FYM) application to soil have clearly shown its benefit to soil fertility, yield enhancement, and soil organic C storage. In an 18-year field experiment in Kenya (23 °C, 970 mm), soil organic C increased by 0.17 ± 0.07 Mg C ha^{-1} yr^{-1} with FYM (10 Mg ha^{-1} yr^{-1}) compared to without FYM (Kapkiyai et al. 1999). Of the C applied in FYM, 9 ± 3% was retained in soil as organic C. Crop yield with FYM (5.3 Mg ha^{-1}) was 61% greater with FYM than without FYM.

In a 45-year field experiment in Nigeria (28 °C, 1070 mm), soil organic C increased by 0.21 ± 0.01 Mg C ha^{-1} yr^{-1} with FYM (5 Mg ha^{-1} yr^{-1}) compared to without FYM (Agbenin and Goladi 1997). In this naturally P-deficient soil, total soil P increased by 12 ± 12 kg ha^{-1} yr^{-1} with FYM.

In a 30-year field experiment at Ranchi, India (23 °C, 1450 mm), soil organic C was greater with FYM (3.9 g kg^{-1}) than without FYM (3.3 g kg^{-1}) (Manna et al. 2007). Total soil N was also 17% greater with FYM than without FYM application.

However, soybean and wheat yields were generally not affected by FYM application. In a 30-year field experiment at Hawalbagh, India (1035 mm), soil organic C increased by 0.56 ± 0.02 Mg C ha^{-1} yr^{-1} with FYM (10 Mg ha^{-1} yr^{-1}) compared to without FYM (Kundu et al. 2007). Above-ground crop biomass production with FYM (6.4 Mg ha^{-1}) was 2.4 times greater than without FYM application.

In a 22-year field experiment in Italy (14 °C, 760 mm), soil organic C increased by 0.20 Mg C ha^{-1} yr^{-1} with FYM (7.5 Mg ha^{-1} yr^{-1}) compared to without FYM (Govi et al. 1992). Soil humification index increased to 60% with FYM compared to 51% without FYM.

In a 20-year study of pearl millet–wheat cropping in India (26 °C, 440 mm), soil organic C increased with increasing FYM application rate. However as a percentage of C applied in FYM, increasing FYM application rate led to less efficient retention of C in soil (Gupta et al. 1992).

Reviewing the climatic influence of animal manure application on soil organic C storage, temperature regime appears to have a greater impact than precipitation regime. Retention of C in soil was 23 + 15% of C applied from animal manure in temperate or frigid regions, but was only 7 + 5% in thermic regions. Moist regions retained 8 + 4% of C applied with animal manure, while dry regions retained 11 + 14%. These data are consistent with environmental controls on soil microbial activity and suggest that future research will require increasing acknowledgement of the linkage between climate and potential C sequestration.

4.2.4 Green-Manure Cropping Systems

Green manures are used to build soil fertility, often with plant species having the capacity to fix nitrogen from the atmosphere through root associations with nitrogen fixing bacteria. The C contained in green manure biomass following its termination can be subsequently stored in soil organic matter.

On an abandoned brick-making site in southeastern China (16.5 °C, 1600 mm), planting of ryegrass as an understory crop under China fir for 7 years resulted in soil organic C sequestration of 0.36 ± 0.40 Mg C ha^{-1} yr^{-1} (Zhang and Fang 2007). With soybean as a green manure for 8 years in Columbia (27 °C, 2240 mm), maize yield with green manure (4.2 Mg ha^{-1}) was 20% greater than without green manure (Basamba et al. 2006). Soil organic C did not change during the 8 years of green manuring, probably because of rapid decomposition caused by abundant precipitation, warm temperature, and nutritious residue quality.

At the end of 12 years of Sesbania green manuring in India (24 °C, 715 mm), soil organic C sequestration was 0.09 ± 0.03 Mg C ha^{-1} yr^{-1} (Singh et al. 2007). At the end of 13 years of wheat/soybean–maize cropping with and without vetch as a green manure cover crop in southern Brazil (21 °C, 1740 mm), soil organic C sequestration was −0.30

± 0.15 Mg C ha^{-1} yr^{-1} under conventional tillage and 0.66 ± 0.26 Mg C ha^{-1} yr^{-1} under zero tillage (Sisti et al. 2004). These data suggest that climatic conditions, green manure nutrient quality, and placement in the soil are all important considerations in affecting soil organic C change with green manuring.

4.2.5 Improved Grassland Management

Degradation of permanent grasslands can occur from accelerated soil erosion, compaction, drought, and salinization. Strategies to sequester soil organic C in grasslands must, by necessity, improve the quality of grasslands. Strategies for restoration should include:

- Enhancing soil cover
- Improving soil structure to minimize water runoff and soil erosion

Achieving a balance between agricultural harvest and environmental protection is needed (i.e., stocking density should be optimized). On an oak-grassland in central Texas USA (18°C, 440 mm), water infiltration was highly related to percent ground cover. However, cattle stocking density played an even larger role in controlling water infiltration with time.

Establishment of bermudagrass pasture following long-term cropping in Georgia USA (16°C, 1250 mm) resulted in significant soil organic C accumulation during the first 8 years of management. How forage was managed had a large impact on the rate of soil organic C accumulation during the first 5 years, e.g. soil organic C sequestration rate was 0.30 Mg C ha^{-1} yr^{-1} when forage was removed as hay, 0.65 Mg C ha^{-1} yr^{-1} when forage remained unharvested, and 1.40 Mg C ha^{-1} yr^{-1} when forage was grazed moderately to moderately heavy by cattle during the summer (Franzluebbers et al. 2001).

4.2.6 Cropland-Grazing land Rotation

Opportunities exist to capture a greater quantity of C from crop and grazing systems when the two systems are integrated, because:

- Ligno-cellulosic plant materials can be utilized by ruminant animals
- Manure is deposited directly on the land

- Weeds can be managed with management rather than chemicals

Especially when combined with conservation-tillage cropping, significant potential exists to avoid loss of soil organic C that can accumulate during a perennial pasture phase. In Uruguay, soil erosion averaged 19 Mg ha^{-1} under conventional-tillage continuous cropping, 7 Mg ha^{-1} under conventional-tillage crop–pasture rotation, 3 Mg ha^{-1} under no-tillage continuous cropping, and <2 Mg ha^{-1} under under no-tillage crop–pasture rotation (Garcia-Prechac et al. 2004). Soil or ganic C with crop–pasture rotation was also greater than with continuous cropping in both tillage systems. In the long-term, crop yield was enhanced with crop–pasture rotation than with continuous cropping, especially with no tillage (Garcia-Prechac et al. 2004).

In Argentina, rotations with <7 years of conventional-tillage cropping alternated with >3 years of perennial pasture were able to maintain soil organic C and other important soil properties within acceptable limits to avoid degradation (Studdert et al. 1997). Diaz-Zorita et al. (2002) found that cattle grazing in crop–pasture rotations compacted surface soil only under conventional tillage, but not under no tillage. The ability of soil to resist compaction under no tillage was attributed to greater structural stability.

In warm-moist climatic regions of the world, sufficient opportunities exist to integrate crops and livestock to achieve greater agricultural sustainability through enhanced nutrient cycling, better pest control, and diversification of agricultural enterprises (Katsvairo et al. 2006, Franzluebbers 2007).

4.2.7 Optimal Fertilization

Fertilization of crops is often needed to overcome deficiencies in nutrients supplied by soils, especially in soils exhausted by years of (a) soil erosion, (b) intensive disturbance with tillage, and (c) continuous harvest of products that remove large quantities of nutrients. On the other hand, excessive fertilization can occur when maximum agronomic prescriptions exist without regard for economic and environmental consequences. Today, the C cost of fertilization has become increasingly scrutinized (Schlesinger 1999; Izaurralde et al. 2000).

In a review of data available from the warm-moist climatic region of the southeastern USA, there was a positive response of soil organic C with the application of N fertilizer. The mean N fertilizer rate to achieve maximum soil organic C sequestration was 171 kg N ha^{-1} yr^{-1}, within the range of values often reported to maximize plant yield. However, when considering the C cost of N fertilizer (i.e. C costs of manufacture, distribution, and application), the optimum N fertilizer rate was 107-120 kg N ha^{-1} yr^{-1} based on C costs of 0.98 to 1.23 kg C kg^{-1} N fertilizer (Izaurralde et al. 1998, West and Marland 2002). Also accounting for the global warming potential of assumed N2O emission associated with N fertilizer application (1.586 kg C kg^{-1} N fertilizer; IPCC 1997), optimum N fertilization to maximize C offset would then be reduced to 24-37 kg N ha^{-1} yr^{-1} to achieve soil organic C sequestration of 0.07-0.11 Mg C ha^{-1} yr^{-1} (Franzluebbers 2005).

5 Adapting restoration of degraded land to climate change

Source: Biringer, J., and Lara J. Hansen J. L., (2005) Restoring Forest Landscapes in the Face of Climate Change. In Mansourian, S., Vallauri, D., Dudley, N., Forest Restoration in Landscapes - Beyond Planting Trees, pp. 31-41, Springer.

After completing vulnerability analysis to determine how a forest system may be impacted by changing climatic conditions, the next step is to look at the range of adaptation options available in order to promote resilience.

An effective vulnerability analysis will determine which components of the system—species or functions, for example—will be most vulnerable to change, together with consideration of which parts of the system are crucial for ecosystem health. An array of options pertinent to adapting forests to climate change are available, both to apply to forest communities at high risk from climate change impacts as well as for those whose protection should be prioritised given existing resilience. Long-term resilience of species will be enabled where natural adaptation processes such as migration, selection, and change in structure are allowed to take place due to sufficient connectivity and habitat size within the landscape.

Restoration can provide a series of critical interventions to reduce climate change impacts. Basic tenets of restoration for adaptation include working on a larger scale to increase the amount of available options for ecosystems, inclusion of corridors for connectivity between sites, inclusion of buffers, and provision of heterogeneity within the restoration approach. Key approaches are as follows:

Reduce fragmentation and provide connectivity: Noss (2000) provides an overview of the negative effects of ecosystem fragmentation, which are abundantly documented worldwide. "Edge effects" threaten the microclimate and stability of a forest as the ratio of edge to interior habitat increases. Eventually, the ability of a forest to withstand debilitating impacts is broken. Fragmentation of forest ecosystems also contributes to a loss of biodiversity as exotic, weedy species with high dispersal capacities are favoured and many native species are inhibited by isolation. Restoration strategies should therefore often focus first on those areas where intervention can connect existing forest fragments into a more coherent whole.

Provide buffer zones and flexibility of land uses: The fixed boundaries of protected areas are not well suited to a dynamic environment unless individual areas are extremely large. With changing climate, buffer zones might provide suitable conditions for species if conditions inside reserves become unsuitable. Buffer zones increase the patch size of the interior of the protected area and overlapping buffers provide migratory possibilities for some species. Buffer zones should ideally be large, and managers of protected areas and surrounding lands must demonstrate considerable flexibility by adjusting land management activities across the landscape in response to changing habitat suitability. A specific case for a buffer zone surrounding tropical montane cloud forests can be made based on research that shows that the upwind effects to deforestation of lowland forests causes the cloud base to rise. Restoring forest around protected areas, for example to supply timber through continuous cover forestry, or for nontimber forest products, watershed protection, or as recreational areas, could help maintain the quality of the protected area in the face of climate change.

Maintain genetic diversity and promote ecosystem health via restoration: Adaptation to climate change via selection of resilient species depends on genetic variation. Efforts to maintain genetic diversity should be applied, particularly in degraded landscapes or within populations of commercially important trees (where genetic diversity is often low due to selective harvesting). In such places where genetic diversity has been reduced, restoration, especially using seed sources from lower elevations or latitudes, can play a vital role in maintaining ecosystem resilience. Hogg and Schwarz (1997) suggest that assisted regeneration could be used in southern boreal forests in Canada where drier conditions may decrease natural regeneration of conifer species. Similarly, genotypes of beach pine forests in British Columbia may need assistance in redistributing across the landscape in order to maintain long-term productivity. In addition, species that are known to be more resilient to impacts in a given landscape can be specifically selected for replanting. For example, trees with thick bark can be planted in areas prone to fire to increase tree survival during increased frequency and severity of fires.

6 Financial mechanisms to promote restoration of degraded land in the context of climate change

Source: Kirsten Schuyt, Opportunities for long term financing of forest restoration in landscapes. In Mansourian, S., Vallauri, D., Dudley, N., Forest Restoration in Landscapes - Beyond Planting Trees, pp. 161-176, Springer.

6.1 Introduction

The economic, social, and biodiversity values of forests are increasingly being recognised, and many countries have understood the need to better manage their forest resources. At the same time, in 1997 the Intergovernmental Panel on Forests (IPF) found that domestic financial resources were insufficient to achieve sustainable management, development, or conservation of forests. With the threat of worsening forest depletion in many parts of the world leading to further degradation of forest goods and services, it is recognised that there is a critical need to explore new and innovative ways of financing improved forest management and conservation, including the restoration of forest resources.

Forest landscape restoration is a long-term process and will generally require sustained sources of funding. All too often, overreliance on grants means that funds can only be obtained for short-term projects, and a long term-effort such as the restoration of forests suffers. Grants, however, are not the only source of funding, and a number of options for long-term financing of forest landscape restoration are highlighted below. Traditional financing sources for forestry in developing countries have been domestic public and private, foreign public and private, and international organisations, including NGOs. Depending on the objective of the forestry activities (environmental conservation, subsistence needs for local people, commercial purposes), different financing sources have been sought. However, global financing trends in general are changing, and a wave of economic liberalisation is providing impetus for increased private sector participation. These trends allow for new financing opportunities from the private sector for restoration activities. In light of declining external public funding and weak prospects for new and additional public funding of overseas development assistance in forestry, private capital flows represent potential opportunities for restoration initiatives.

The key to financing opportunities from both private and public funding sources for landscape-scale forest restoration lies in recognising its full economic and financial value. This requires estimating and recognising the economic values of forests and therefore recognising the benefits provided by restoring these forest values. The restoration or loss of these values can then be more realistically weighted against other possible uses of the land. In a landscape context, it then becomes possible to better select areas within the landscape for different uses, allowing a potentially more complete range of values and benefits to be offered. This also requires proper pricing of forest goods and services and setting up mechanisms where money is transferred to pay these prices.

One way to do this is by selling environmental services of forests, such as carbon sequestration, watershed protection, and biodiversity, to finance restoration—a mechanism called payments for environmental services (PES). The PES mechanisms ensure that those who supply environmental services are paid by those who use these services. These range from public payments to self-organised private deals. For example, private companies such as downstream bottling companies pay upstream communities for sustainably managing the forests in the watershed that provide services such as watershed protection on which the bottling companies depend. At the basis of sustainable watershed management should be restoration, where the key is convincing investors that such activities will ensure sustainable environmental services as sustainable "production inputs," thereby making landscape scale restoration financially and economically attractive. Another example of PES is paying for carbon sequestration; energy companies could invest money in restoration projects to increase the carbon sequestration service of forests for the purpose of meeting their carbon offsets, as is allowed under the Kyoto protocol.

6.2 Financing sources

6.2.1 Financing from Domestic Public Sources

General strategies to increase public sources for large-scale restoration involve activities like improving expenditure policies on forestry, reforming macroeconomic policies (including taxes and subsidies), and putting in place new incentives, subsidies, and technical and institutional changes to support restoration that provides wider benefits. It is, however, also important to improve the administrative capacity of forestry agencies themselves to increase their efficiency to collect revenue and to use the resources efficiently for restoration. Other ways to increase forest revenues from public funding are to ensure the proper pricing of forest goods and services (through charges, policies that demand full-cost pricing, permits, licensing, etc.) or setting up special forest trust funds with earmarked taxes to finance specific restoration activities. It is also possible to use tax measures that tax downstream beneficiaries to fund restoration upstream.

6.2.2 Multilateral and Bilateral Donors

Given the declining trend in ODA, efforts must be directed at maintaining current funds from multi- and bilateral aid. In general, however, environment is no longer a top priority of development and cooperation agencies, and it has now been mainstreamed in all development activities under the new sector approach embraced by many donor agencies. Therefore, successful proposals for forest landscape restoration from multilateral and bilateral donors increasingly need to explain how forest landscape restoration activities will address poverty alleviation. Furthermore, it is also useful to use ODA to leverage private funding for restoration. The World Bank's Sustainable Forest Market Transformation Initiative (SFMTI) is a good example, which promotes private sector participation in forest management.

6.2.3 Private Not-for-Profit Sources

Private not-for-profit sources include financing channelled from local communities, international foundations, and NGOs for forest landscape restoration activities. International NGOs have become important for providing new financing mechanisms, of which environment trust funds or foundations are particularly interesting for providing financing to natural resource management in general. Trust funds are not philanthropic foundations. Rather, they raise money to carry out their own programmes and have specific missions and interests and sometimes geographical focusses. The main purpose of setting up a trust fund has traditionally been to provide long-term stable funding for national parks and other protected areas or small grants to local NGOs and community groups for projects aimed at conserving biodiversity and using natural resources more sustainably. Such trust funds could be set up to support the restoration of forest values over the long term.

6.2.4 Private for-Profit Sources

Private for-profit sources range from mobilising households to invest in restoration to investments from large international corporations. Household investments will have an effect only if the projects offer short-term benefits with an acceptable level of risk. These benefits can be an increased income for households or indirect payments in, for example, alternative livelihoods, roads, schools, and so on. On the other hand, a more grant-type of financing from large private companies like dam, oil, plantation, and mining companies can be mobilised to pay for forest restoration as compensation for environmental disruption they may cause. This motivation may also come from business ethics and thus be part of a company's public relations campaign. An example is where environmental NGOs are invited by a plantation company to restore part of their land according to standards compatible with forest landscape restoration. Lastly, engaging conventional capital markets by channelling capital toward forest management and restoration has potential.

6.2.5 Payments for Forest Goods and Services

Market-based financing has both potentials and limitations but it does provide real opportunities for mobilising funds for forest landscape restoration. A good example of payments for environmental goods is the certification body, the Forest Stewardship Council (FSC), which developed a market for sustainably produced wood and wood products that come with a seal of approval or certificate. In terms of payments for environmental services, a good example is the increase in projects that create payment mechanisms where downstream beneficiaries pay for the sustainable management of forests upstream. Such systems provide significant opportunities for innovative funding for forest landscape restoration.

6.2.6 International Systems of Payments for the Environmental Commons

There has been some progress at international level to pay for the global commons. The best known is the Global Environmental Facility (GEF), which provides partial grant funding to eligible countries for projects that address threats to the environment in four areas: biodiversity loss, climate change, ozone depletion, and degradation of international waters. Under its biodiversity programme, the GEF can support conservation and sustainable use of significant biodiversity, including forest ecosystems.

Funding from GEF for forest landscape restoration could be mobilised under this area. In a landscape context, it will be possible to initiate a restoration activity with public funding in order to address immediate livelihood needs (e.g., provision of traditional medicines, reduction in people's vulnerability). In the longer term, and still within the context of landscapes and the restoration of many forest benefits, it may become possible to ensure sustained funding by the private sector in order to meet additional benefits (such as certified nontimber forest products, for instance).

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Chapter

9

Research Matters – Climate Change Governance

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Chapter 9

Research Matters – Climate Change Governance

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1 Scientific basis of climate change

"*Climate change* in IPCC usage refers to any change in climate over time, whether due to natural variability or as a result of human activity. This usage differs from that in the Framework Convention on Climate Change, where climate change refers to a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods". In figure 1 is shown the anthropogenic drivers, impacts of and responses to climate change, and their linkages (Source: IPCC, 2007).

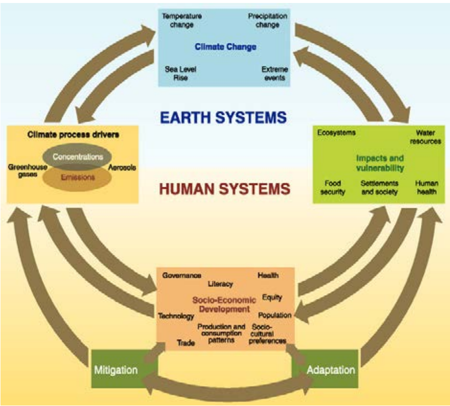

Figure 1. (Source: IPCC, 2007) The anthropogenic drivers, impacts of and responses to climate change, and their linkages.

1.1 Observations of climate change

As a result of human activities, since 18th century, the concentrations of carbon dioxide, methane and nitrous oxide increased gradually. These evidences were obtained studying ice cores. The main causes of global increase of carbon dioxide concentration were fossil fuel and land-use change. On the other hand, agriculture was the main source of concentration increase for methane and nitrous oxide. This increase of concentration for the mentioned gases created a greenhouse effect with climate warming consequences.

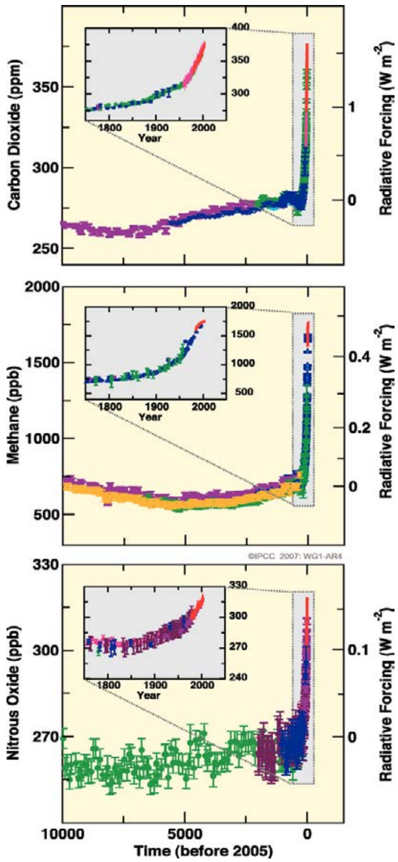

Figure 2. *(Source: IPCC, 2007) The trend of carbon dioxide, methane and nitrous oxide concentrations over the last 10,000 years [Red lines – based on atmospheric samples; other colors – based on ice cores (different for each study)]*

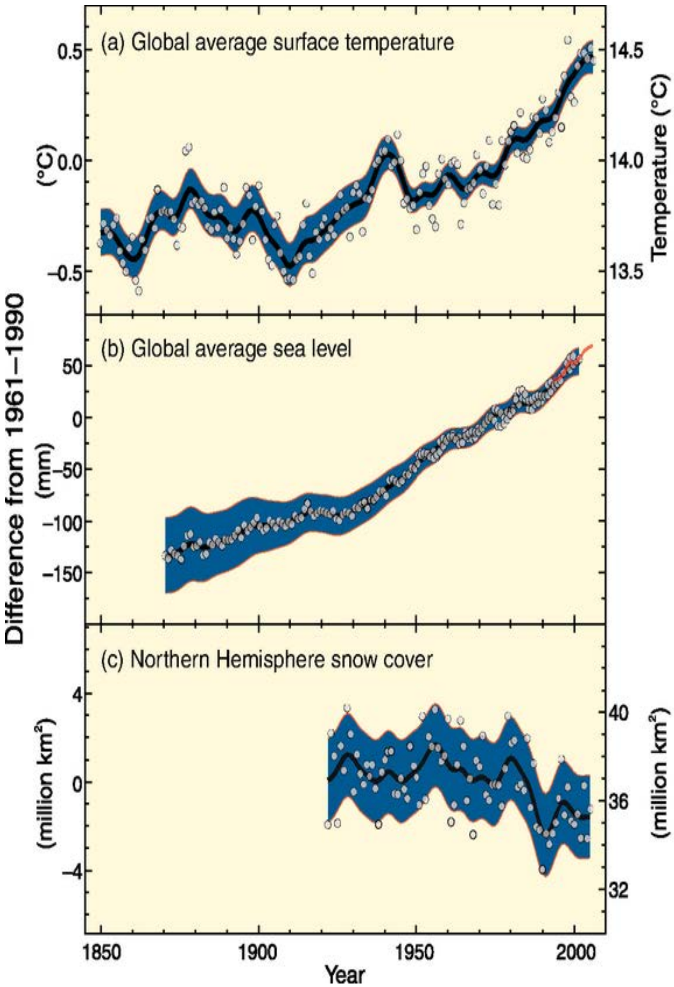

Figure 3. *(source: IPCC, 2007) The changes in global average surface temperature (a), global average sea level (b) and Northern Hemisphere snow cover (c), between 1961 and 1990.*

Carbon dioxide is the most important greenhouse gas. The concentration of carbon dioxide into the atmosphere increased from 280 ppm in the pre-industrial times to 379 ppm in 2005 (figure 2). Therefore the concentration of carbon dioxide increased about 35% by human activities especially industrialization. The global atmospheric concentration of methane has increased from 715 ppb in pre-industrial times to about

1774 ppb in 2005, which means an increase of 148%. Also, the global atmospheric nitrous oxide concentration increased from 270 ppb in pre-industrial times to 319 ppb in 2005. The growth rate remained constant since 1980. Many halocarbons (including hydrofluorocarbons) have increased from a near-zero pre-industrial background concentration, primarily due to human activities.

Warming of the climate is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, rising of sea level and melting of snow and ice. Moreover, eleven of the last twelve years (1995–2006) rank among the 12 warmest years in the last 150 years. The warming trend over the last 50 years is about 0.13°C per decade. The temperature increased from 1850 to 2005 by about 0.76°C.

Considering all observations made until this moment, it is extremely unlikely that global climate change over the last 50 years can be put on the basis of natural causes alone. It is very likely that there has been significant anthropogenic warming over the past 50 years. The observed patterns of warming, including greater warming over land than over the ocean, and their changes over time, are only simulated by models that include anthropogenic forcing. Also, the temperatures of the most extreme hot nights, cold nights and cold days are likely to have increased due to anthropogenic forcing.

The observed patterns of warming, including greater warming over land than over the ocean, and their changes over time, are simulated only by models that include anthropogenic forcing. No coupled global climate model that has used natural forcing only has reproduced the continental mean warming trends in individual continents (except Antarctica) over the second half of the 20th century (figure 4).

1.2 Observed effects of climate change

There is high confidence that natural systems related to snow, ice and frozen ground (including permafrost) are affected. Examples are:

- enlargement and increased numbers of glacial lakes
- increasing ground instability in permafrost regions and rock avalanches in mountain regions
- changes in some Arctic and Antarctic ecosystems, including those in sea-ice biomes, and predators at high levels of the food web.

Based on growing evidence, there is high confidence that the following effects on hydrological systems are occurring: increased runoff and earlier spring peak discharge in many glacier- and snow-fed rivers, and warming of lakes and rivers in many regions, with effects on thermal structure and water quality.

There is very high confidence, based on more evidence from a wider range of species, that recent warming is strongly affecting terrestrial biological systems, including such changes as earlier timing of spring events, such as leaf-unfolding, bird migration and egg-laying; and pole ward and upward shifts in ranges in plant and animal species. Based on satellite observations since the early 1980s, there is high confidence that there has been a trend in many regions towards earlier 'greening' of vegetation in the spring linked to longer thermal growing seasons due to recent warming.

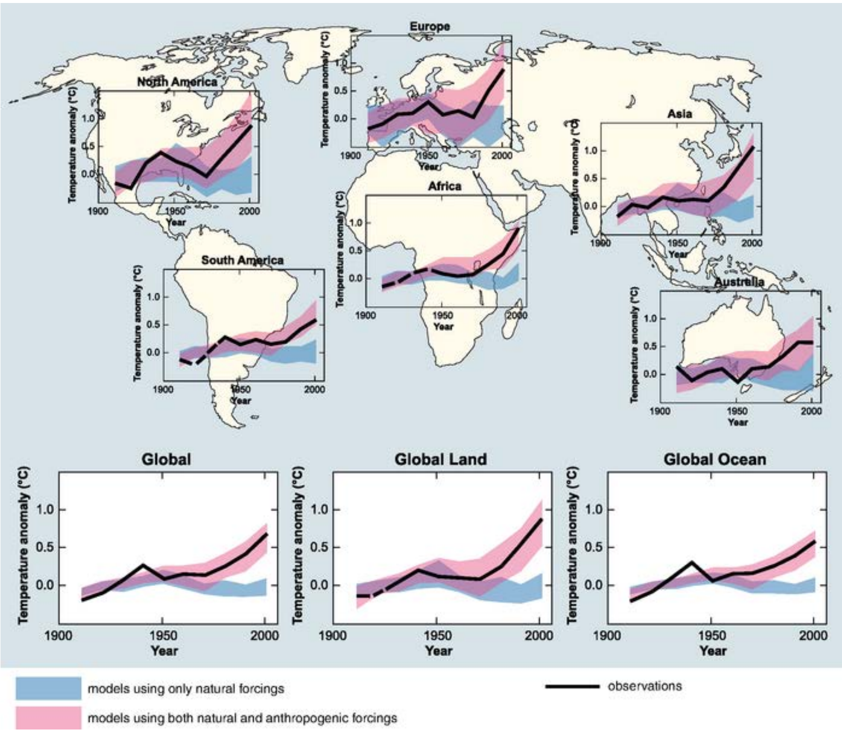

Figure 4. *(Source: IPCC, 2007) Climate model predictions using only natural forcing (blue) and both natural and anthropogenic forcing (red), with the decadal averages of observations (black line, dashed lines where spatial coverage is less than 50%)*

There is high confidence, based on substantial new evidence, that observed changes in marine and freshwater biological systems are associated with rising water temperatures, as well as related changes in ice cover, salinity, oxygen levels and circulation. These include: shifts in ranges and changes in algal, plankton and fish abundance in high-latitude oceans; increases in algal and zooplankton abundance in high-latitude and high-altitude lakes; and range changes and earlier fish migrations in rivers. While there is increasing evidence of climate change impacts on coral reefs, separating the impacts of climate-related stresses from other stresses (e.g. over-fishing and pollution) is difficult.

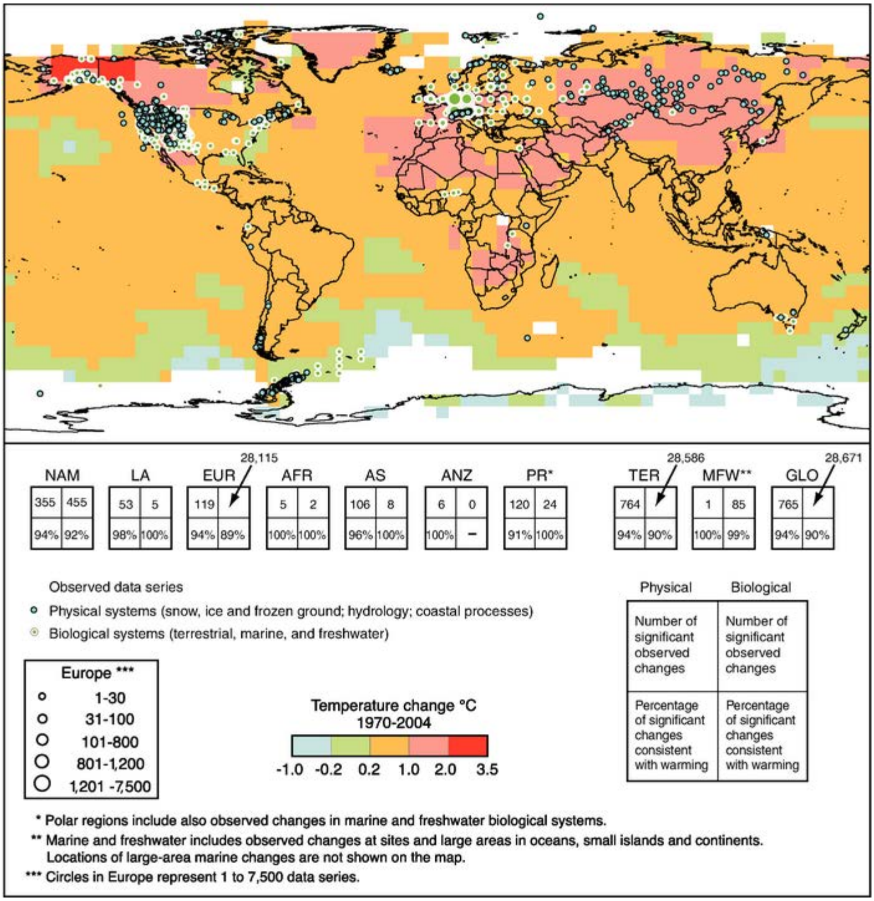

Figure 5. *(Source: IPCC, 2007) Changes in physical and biological systems and surface temperature 1970-2004*

1.3 Emission scenarios

For the next 20 years, the temperature is about to increase of about 0.2°C per decade. Even if the concentrations of all greenhouse gases and aerosols had been kept constant at year 2000 levels, a further warming of about 0.1°C per decade would be expected. Continued greenhouse gas emissions at or above current rates are going to cause further warming and induce many and more severe changes in the global climate system.

The IPCC Special Report on Emissions Scenarios (SRES, 2000) projects an increase of global GHG emissions by 25 to 90% (CO2-eq) between 2000 and 2030 (Figure 6), with fossil fuels maintaining their dominant position in the global energy mix to 2030 and beyond. More recent scenarios without additional emissions mitigation are comparable in range.

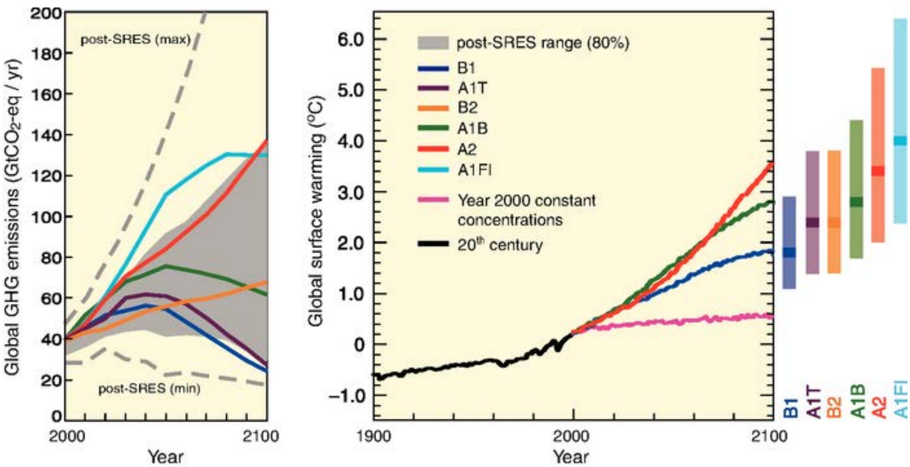

Figure 6. *Source: (IPCC, 2007) Left chart: Global GHG emissions (in GtCO2-eq) in the absence of climate policies; Right chart: Multi-model global averages of surface warming for different scenarios*

The key uncertainties of the drivers and projections of future climate changes and their impacts as presented in Climate Change 2007 - Synthesis report are:

- Uncertainty in the equilibrium climate sensitivity creates uncertainty in the expected warming for a given CO_2-eq stabilization scenario. Uncertainty in the carbon cycle feedback creates uncertainty in the emissions trajectory required to achieve a particular stabilization level.
- Models differ considerably in their estimates of the strength of different feedbacks in the climate system, particularly cloud feedbacks, oceanic heat uptake and carbon cycle feedbacks, although progress has been made in these areas. Also, the confidence in projections is higher for some variables (e.g. temperature) than for others (e.g. precipitation), and it is higher for larger spatial scales and longer time averaging periods.
- Aerosol impacts on the magnitude of the temperature response, on clouds and on precipitation remain uncertain.
- Future changes in the Greenland and Antarctic ice sheet mass, particularly due to changes in ice flow, are a major source of uncertainty that could increase sea level rise projections. The uncertainty in the penetration of the heat into the oceans also contributes to the future sea level rise uncertainty.
- Large-scale ocean circulation changes beyond the 21st century cannot be reliably assessed because of uncertainties in the melt water supply from the Greenland ice sheet and model response to the warming.
- Projections of climate change and its impacts beyond about 2050 are strongly scenario and model-dependent, and improved projections would require improved understanding of sources of uncertainty and enhancements in systematic observation networks.
- Impacts research is hampered by uncertainties surrounding regional projections of climate change, particularly precipitation.
- Understanding of low-probability/high-impact events and the cumulative impacts of sequences of smaller events, which is required for risk-based approaches to decision-making, is generally limited.

2 The international response to climate change

Climate change was internationally recognized as a serious problem in February 1979 in Geneva when the First World Climate Conference sponsored by the WMO took place (Robledo & Masera, 2007). In response to this issue, an international environmental treaty named United Nations Framework Convention on Climate Change was adopted by the United Nations Conference on Environment and Development (UNCED) at the “Rio Earth Summit” in 1992. After five years, within this convention was adopted Kyoto Protocol, that established legally binding emissions targets for industrialized countries, and created innovative mechanisms to assist these countries in meeting these targets. Recognizing the needs of policymakers for authoritative and up-to-date scientific information, the World Meteorological Organization (WMO) and the UN Environmental Programme (UNEP) established the Intergovernmental Panel on Climate Change (IPCC) in 1988 (Robledo & Masera, 2007).

2.1 Intergovernmental Panel on Climate Change (IPCC)

(Source: www.ipcc.org)

The Intergovernmental Panel on Climate Change was created in 1988. It was set up by the World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP) as an effort by the United Nations to provide the governments of the world with a clear scientific view of what is happening to the world’s climate. The initial task for the IPCC as outlined in the UN General Assembly Resolution 43/53 of 6 December 1988 was to prepare a comprehensive review and recommendations with respect to the state of knowledge of the science of climate change; social and economic impact of climate change, possible response strategies and elements for inclusion in a possible future international convention on climate. Today the IPCC’s role is also, as defined in Principles Governing IPCC Work, “...to assess on a comprehensive, objective, open and transparent basis the scientific, technical and socio-economic information relevant to understanding the scientific basis of risk of human-induced climate change, its potential impacts and options for adaptation and mitigation. IPCC reports should be neutral with respect to policy, although they may need to deal objectively with scientific, technical and socio-economic factors relevant to the application of particular policies.”

The scientific evidence brought up by the first IPCC Assessment Report of 1990 unveiled the importance of climate change as a topic deserving a political platform among countries to tackle its consequences. It therefore played a decisive role in leading to the creation of the United Nations Framework Convention on Climate Change (UNFCCC), the key international treaty to reduce global warming and cope with the consequences of climate change.

Since then the IPCC has delivered on a regular basis the most comprehensive scientific reports about climate change produced worldwide, the Assessment Reports. It also continued to respond to the need of the UNFCCC for information on scientific technical matters through Special Reports, Technical Papers and Methodology Reports. Methodologies and guidelines were prepared to help Parties under the UNFCCC in preparing their national greenhouse gas inventories.

The IPCC Second Assessment Report of 1995 provided key input in the way to the adoption of the Kyoto Protocol in 1997. The Third Assessment Report came out in 2001, and the Fourth in the course of 2007. "Climate Change 2007", clearly brought to the attention of the world the scientific understanding of the present changes in our climate and led the organization to be honored with the Nobel Peace Prize at the end of that same year.

Along with Comprehensive Assessment Reports, the IPCC has produced several Special Reports on various topics of growing interest, and many other papers and contributions to the advancements of the climate change science.

The participation of the scientific community in the work of the IPCC has been growing greatly, both in terms of authors and contributors involved in the writing and the reviewing of the reports and of geographic distribution and topics covered by the reports.

The IPCC is an intergovernmental body. It is open to all member countries of the United Nations (UN) and WMO. Currently 195 countries are members of the IPCC. Governments participate in the review process and the plenary Sessions, where main decisions about the IPCC work programme are taken and reports are accepted, adopted and approved. The IPCC Bureau Members, including the Chair, are also elected during the plenary Sessions.

Because of its scientific and intergovernmental nature, the IPCC embodies a unique opportunity to provide rigorous and balanced scientific information to decision makers. By endorsing the IPCC reports, governments acknowledge the authority of their scientific content. The work of the organization is therefore policy-relevant and yet policy-neutral, never policy-prescriptive.

2.1.1 The structure of IPCC

(Source: www.ipcc.org)

The IPCC is currently organized in 3 Working Groups and a Task Force. They are assisted by Technical Support Units (TSU), which are hosted and financially supported by the Government of the developed country co-chair of that Working Group/Task Force:

- Working Group I - *The Physical Science Basis of Climate Change* - Assesses the physical scientific aspects of the climate system and climate change. The main topics assessed by WG I include: changes in greenhouse gases and aerosols in the atmosphere; observed changes in air, land and ocean temperatures, rainfall, glaciers and ice sheets, oceans and sea level; historical and paleoclimatic perspective on climate change; biogeochemistry, carbon cycle, gases and aerosols; satellite data and other data; climate models; climate projections, causes and attribution of climate change.
- Working Group II - *Climate Change Impacts, Adaptation and Vulnerability* - Assesses the vulnerability of socio-economic and natural systems to climate change, negative and positive consequences of climate change, and options for adapting to it. It also takes into consideration the inter-relationship between vulnerability, adaptation and sustainable development. The assessed information is considered by sectors (water resources; ecosystems; food & forests; coastal systems; industry; human health) and regions (Africa; Asia; Australia & New Zealand; Europe; Latin America; North America; Polar Regions; Small Islands).
- Working Group III - *Mitigation of Climate Change* - Assesses options for mitigating climate change through limiting or preventing greenhouse gas emissions and enhancing activities that remove them from the atmosphere. The main economic sectors are taken into account, both in a near-term and in a long-term perspective. The sectors include energy, transport, buildings,

industry, agriculture, forestry, waste management. The WG analyses the costs and benefits of the different approaches to mitigation, considering also the available instruments and policy measures. The approach is more and more solution-oriented.

Working Groups also meet at the Plenary at the level of Representatives of Governments. The main objective of the Task Force on National Greenhouse Gas Inventories is to develop and refine a methodology for the calculation and reporting of national GHG emissions and removals. In addition to the Working Groups and Task Force, further Task Groups and Steering Groups may be established for a limited or longer duration to consider a specific topic or question.

2.1.2 Task Force on National Greenhouse Gas Inventories (TFI)

The TFI was established by the IPCC, at its 14th session (October 1998), to oversee the IPCC National Greenhouse Gas Inventories Programme (IPCC-NGGIP). This programme had been undertaken since 1991 by the IPCC WG I in close collaboration with the Organization for Economic Co-operation and Development (OECD) and the International Energy Agency (IEA). In 1999, the Technical Support Unit (TSU) set up at the Institute for Global Environmental Strategies (IGES) in Japan took over this programme in accordance with a decision taken by the IPCC at its 14th session.

The objectives of the TFI are:

- to develop and refine an internationally-agreed methodology and software for the calculation and reporting of national GHG emissions and removals, and
- to encourage the widespread use of this methodology by countries participating in the IPCC and by signatories of the United Nations Framework Convention on Climate Change (UNFCCC).

2.1.3 Assessment reports

The IPCC has published four comprehensive assessment reports reviewing the latest climate science, as well as a number of special reports on particular topics. These reports are prepared by teams of relevant researchers selected by the Bureau from government nominations.

The IPCC reports were published:

- 1990 - the first assessment report, with a supplementary report in 1992,
- 1995 - the second assessment report (SAR)
- 2001 - the third assessment report (TAR)
- 2007 - fourth assessment report (AR4)

The fifth assessment report is due to be issued in 2014.

Each assessment report is in three volumes, corresponding to Working Groups I, II and III. Unqualified, "the IPCC report" is often used to mean the Working Group I report, which covers the basic science of climate change.

2.2 United Nations Framework Convention on Climate Change (UNFCCC)

(Source: www.unfccc.int)

In 1992, countries joined an international treaty, the United Nations Framework Convention on Climate Change, to cooperatively consider what they could do to limit average global temperature increases and the resulting climate change, and to cope with whatever impacts were, by then, inevitable.

By 1995, countries realized that emission reductions provisions in the Convention were inadequate. They launched negotiations to strengthen the global response to climate change, and, two years later, adopted the Kyoto Protocol. The Kyoto Protocol legally binds developed countries to emission reduction targets. The Protocol's first commitment period started in 2008 and ends in 2012. At COP17 in Durban, governments of the Parties to the Kyoto Protocol decided that a second commitment period, from 2013 onwards, would seamlessly follow the end of the first commitment period. The length of the second commitment period is to be determined: it will be either five or eight years long.

There are now 195 Parties to the Convention. The UNFCCC secretariat supports all institutions involved in the international climate change negotiations, particularly the Conference of the Parties (COP), the subsidiary bodies (which advise the COP), and the COP Bureau (which deals mainly with procedural and organizational issues arising from the COP and also has technical functions).

At the very heart of the response to climate change, however, lies the need to reduce emissions. In 2010, governments agreed that emissions need to be reduced so that global temperature increases are limited to below 2 degrees Celsius.

No mandatory limits on greenhouse gas emissions were drawn up. Instead, the treaty provides for updates (called "protocols") that would set mandatory emission limits. The principal update is the Kyoto Protocol, which has become much better known than the UNFCCC itself. The UNFCCC entered into force on 21 March 1994. Today, it has near-universal membership. The 195 countries that have ratified the Convention are called Parties to the Convention.

The ultimate objective of the Convention is to stabilize greenhouse gas concentrations "at a level that would prevent dangerous anthropogenic (human induced) interference with the climate system." It states that "such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened, and to enable economic development to proceed in a sustainable manner."

The first important task of UNFCCC was to establish national greenhouse gas inventories of greenhouse gas (GHG) emissions and removals. These levels were used to create the 1990 benchmark levels for accession of Annex I countries to the Kyoto Protocol. Also, these levels were used for the commitment of those countries to GHG reductions.

The parties to the convention have met annually from 1995 in Conferences of the Parties (COP) to assess progress in dealing with climate change. In 1997, the Kyoto Protocol was concluded and established legally binding obligations for developed countries to reduce their greenhouse gas emissions.

Parties to UNFCCC are classified as:

- Annex I countries: industrialized countries and economies in transition
- Annex II countries: developed countries which pay for costs of developing countries
- Non Annex I countries: Developing countries.

Annex I countries which have ratified the Protocol have committed to reduce their emission levels of greenhouse gasses to targets that are mainly set below their 1990 levels. They may do this by allocating reduced annual allowances to the major operators within their borders. These operators can only exceed their allocations if they buy emission allowances, or offset their excesses through a mechanism that is agreed by all the parties to UNFCCC.

Annex II countries are a sub-group of the Annex I countries. They comprise the OECD members, excluding those that were economies in transition in 1992.

Developing countries are not required to reduce emission levels unless developed countries supply enough funding and technology. Setting no immediate restrictions under UNFCCC serves three purposes:

- it avoids restrictions on their development, because emissions are strongly linked to industrial capacity
- they can sell emissions credits to nations whose operators have difficulty meeting their emissions targets
- they get money and technologies for low-carbon investments from Annex II countries.

Developing countries may volunteer to become Annex I countries when they are sufficiently developed.

2.2.1 Mitigation of climate change

(Source: www.unfccc.int)

Reducing Emissions from Deforestation and forest Degradation (REDD)

The agenda item on "Reducing emissions from deforestation in developing countries and approaches to stimulate action" was first introduced into the COP agenda at its eleventh session in Montreal (December 2005).

The IPCC (2007) estimated emissions from deforestation in the 1990s to be at 5.8 $GtCO_2$/year. It also noted that reducing and/or preventing deforestation and preventing the release of carbon emissions into the atmosphere is the mitigation option with the largest and most immediate carbon stock impact in the short term per hectare and per year globally.

Parties to the UNFCCC process recognized the contribution of greenhouse gas emissions from deforestation in developing countries to climate change and the need to take action to reduce such emissions. After a two-year process, the COP adopted a decision on "Reducing emissions from deforestation in developing countries: approaches to stimulate action" (Decision 2/CP.13). The decision provides a mandate for several elements and actions by Parties relating to reducing emissions from deforestation and forest degradation in developing countries:

- Further strengthening and supporting ongoing efforts;
- Support for and facilitate capacity-building, technical assistance and transfer of technology relating to methodological and technical needs and institutional needs of developing countries;
- Explore a range of actions, identify options and undertake demonstration activities to address drivers of deforestation and enhance forest carbon stocks due to sustainable management of forests; and
- Mobilize resources to support the efforts mentioned above.

The decision also provides a set of indicative guidance for the implementation and evaluation of demonstration activities. Parties are also encouraged to apply the IPCC Good Practice Guidance for Land Use, Land-Use Change and Forestry for estimating and reporting of emissions and removals.

In 2008 and 2009, policy approaches and positive incentives relating to reducing emissions from deforestation and forest degradation in developing countries and the role of conservation, sustainable management of forests, and enhancement of forest carbon stocks in developing countries have been considered under the process of the Bali Action Plan.

UN REDD Programme

(Source: www.un-redd.org/)

The UN-REDD Programme is the United Nations Collaborative initiative on Reducing Emissions from Deforestation and forest Degradation (REDD) in developing countries. The Programme was launched in September 2008 to assist developing countries prepare and implement national REDD+ strategies, and builds on the convening power and expertise of the Food and Agriculture Organization of the United Nations

(FAO), the United Nations Development Programme (UNDP) and the United Nations Environment Programme (UNEP).

The Programme currently supports 44 partner countries spanning Africa, Asia-Pacific and Latin America, of which 16 are receiving support to National Programme activities. These 16 countries are: Bolivia, Cambodia, Democratic Republic of the Congo (DRC), Ecuador, Indonesia, Nigeria, Panama, Papua New Guinea, Paraguay, the Philippines, Republic of Congo, Solomon Islands, Sri Lanka, Tanzania, Viet Nam and Zambia. To-date, the UN-REDD Programme's Policy Board has approved a total of US$67.3 million for National Programmes in these 16 partner countries. These funds help to support the development and implementation of national REDD+ strategies.

UN-REDD Programme countries not receiving direct support to national programmes engage with the Programme in a number of ways, including as observers to the Programme's Policy Board, and through participation in regional workshops and knowledge sharing, facilitated by the Programme's interactive online workspace. These countries are: Argentina, Bangladesh, Benin, Bhutan, Cameroon, Central African Republic, Chile, Colombia, Costa Rica, Ethiopia, Gabon, Ghana, Guatemala, Guyana, Honduras, Ivory Coast, Kenya, Malaysia, Mexico, Mongolia, Myanmar, Nepal, Pakistan, Peru, South Sudan, Sudan, Suriname and Uganda.

Land Use, Land-Use Change and Forestry

(Source: www.unfccc.int)

Forests, through growth of trees and an increase in soil carbon, contain a large part of the carbon stored on land. Forests present a significant global carbon stock. Global forest vegetation stores 283 Gt of carbon in its biomass, 38 Gt in dead wood and 317 Gt in soils (top 30 cm) and litter. The total carbon content of forest ecosystems has been estimated at 638 Gt for 2005, which is more than the amount of carbon in the entire atmosphere. This standing carbon is combined with a gross terrestrial uptake of carbon, which was estimated at 2.4 Gt a year, a good deal of which is sequestration by forests. Approximately half of the total carbon in forest ecosystems is found in forest biomass and dead wood.

Other terrestrial systems also play an important role. Most of the carbon stocks of croplands and grasslands are found in the below-ground plant organic matter and soil.

Human activities, through land use, land-use change and forestry (LULUCF) activities, affect changes in carbon stocks between the carbon pools of the terrestrial ecosystem and between the terrestrial ecosystem and the atmosphere.

Management and/or conversion of land uses (e.g. forests, croplands and grazing lands) affects sources and sinks of CO_2, CH_4 and N_2O. During the decade of the 1990s, deforestation in the tropics and forest re-growth in temperate and boreal zones remained the major factors contributing to emissions and removals of greenhouse gases (GHG) respectively. Estimated CO_2 emissions associated with land-use change, averaged over the 1990s, were 0.5 to 2.7 GtC yr^{-1}, with a central estimate of 1.6 $GtCyr^{-1}$.

The role of LULUCF activities in the mitigation of climate change has long been recognized. Mitigation achieved through activities in the LULUCF sector, either by increasing the removals of GHGs from the atmosphere or by reducing emissions by sources, can be relatively cost-effective.

General mitigation options could include forest-related activities such as reducing emissions from deforestation and degradation, enhancing the sequestration rate in new or existing forests, and using wood fuels and wood products as substitutes for fossil fuels and more energy-intensive materials. A variety of options for mitigation of GHG emissions also exists in other land systems. The most prominent example is agriculture, where options include improved crop and grazing land management (e.g., improved agronomic practices, nutrient use, tillage and residue management), restoration of organic soils that are drained for crop production, and restoration of degraded lands.

However, the main drawback of LULUCF activities is their potential reversibility and non-permanence of carbon stocks as a result of human activities, (with the release of GHG into the atmosphere), disturbances (e.g. forest fires or disease), or environmental change, including climate change.

According to the FAO (2005), deforestation, mainly conversion of forests to agricultural land, continues at an alarming rate of approximately 13 million hectares per year (for the period 1990–2005). Deforestation results in immediate release of the carbon originally stored in the trees as CO_2 emissions (with small amounts of CO and CH_4), particularly if the trees are burned and the slower release of emissions from the decay of organic matter. The IPCC WGIII (2007) estimated emissions from deforestation in the 1990s to be at 5.8 $GtCO_2$/yr. The IPCC also notes that reducing and/or preventing deforestation is the mitigation option with the largest and most immediate carbon stock impact in the short term per hectare and per year globally as the release of carbon as emissions into the atmosphere is prevented.

LULUCF sector under the Convention

Under the Convention, the commitments by Parties to mitigate climate change are defined in Article 4. These commitments take into account Parties' common but differentiated responsibilities and their specific national and regional development priorities, objectives and circumstances. Article 4 has references to commitments relating to the land use, land-use change and forestry sector:

- Article 4, paragraph 1(a): Develop, periodically update, publish and make available to the Conference of the Parties, in accordance with Article 12, national inventories of anthropogenic emissions by sources and removals by sinks of all greenhouse gases (GHGs)[1] not controlled by the Montreal Protocol, using comparable methodologies to be agreed upon by the Conference of the Parties.
- Article 4, paragraph 1(d): Promote sustainable management, and promote and cooperate in the conservation and enhancement, as appropriate, of sinks and reservoirs of all GHGs not controlled by the Montreal Protocol, including biomass, forests and oceans as well as other terrestrial, coastal and marine ecosystems.

LULUCF under the Kyoto Protocol

Several Articles of the Kyoto Protocol make provisions for the inclusion of land use, land-use change and forestry activities by Parties as part of their efforts to implement the Kyoto Protocol and contribute to the mitigation of climate change.

In Article 2, sub-paragraphs 1(a) (ii) and (iii), Annex I Parties, in meeting their emission reduction commitments under Article 3, shall implement and/or further elaborate policies and measures to protect and enhance sinks and reservoirs of greenhouse gases (GHGs) not controlled by the Montreal Protocol, promote sustainable forest management, afforestation and reforestation and sustainable forms of agriculture.

1 Including inventories of GHG emissions and removals from the LULUCF sector

Annex I Parties must report emissions by sources and removals by sinks of GHGs resulting from LULUCF activities, in accordance with Article 3, paragraphs 3 and 4. Under Article 3.3 of the Kyoto Protocol, Parties decided that net changes in GHG emissions by sources and removals by sinks through direct human-induced LULUCF activities, limited to afforestation, reforestation and deforestation that occurred since 1990, can be used to meet Parties' emission reduction commitments. Under Article 3.4 of the Kyoto Protocol, Parties may elect additional human-induced activities related to LULUCF specifically, forest management, cropland management, grazing land management and revegetation, to be included in their accounting of anthropogenic GHG emissions and removals for the first commitment period. Upon election, this decision by a Party is fixed for the first commitment period. The changes in carbon stock and GHG emissions relating to LULUCF activities under Article 3, paragraphs 3 and 4 must be reported for each year of the commitment period, beginning with the start of the commitment period, or with the start of the activity, whichever is later. When LULUCF activities under Articles 3.3 and 3.4 result in a net removal of GHGs, an Annex I Party can issue removal units (RMUs) on the basis of these activities as part of meeting its commitment under Article 3.1.

In addition, under Article 3, paragraph 7, for the purpose of calculating the assigned amount, an Annex I Party for which land-use change and forestry constituted a net source of GHG emissions in 1990 shall include in their 1990 emissions base year or period the aggregate anthropogenic carbon dioxide equivalent emissions by sources minus removals by sinks in 1990 from land-use change [according to paragraph 5(b) in the annex to 13/CMP.1, this refers to: all emissions by sources minus removals by sinks reported in relation to the conversion of forests (deforestation)].

Two of the flexible mechanisms of the Kyoto Protocol make provisions for the implementation of LULUCF project activities by Parties. The clean development mechanism (CDM) under the Kyoto Protocol (Article 12) allows for the implementation of LULUCF project activities, limited to afforestation and reforestation, in non-Annex I countries. These project activities assist Annex I Parties in achieving compliance with their emission reduction commitments under Article 3, while simultaneously assisting non-Annex I Parties to achieve sustainable development.

Under joint implementation (Article 6), an Annex I Party may implement projects that increase removals by sinks in another Annex I country. The emissions reduction units (ERUs) generated from such a project can be used by the former to meet its emission reduction target. Any project under Article 6 aimed at enhancing anthropogenic removals by sinks shall conform to definitions, accounting rules, modalities and guidelines under Article 3, paragraphs 3 and 4, of the Kyoto Protocol.

2.2.2 Reporting GHG inventories

(Source: www.unfccc.int)

The quality and credibility of GHG inventories rely on the integrity of the methodologies used, the completeness of reporting, and the procedures for compilation of data. To promote the provision of credible and consistent GHG information, the Conference of Parties (COP) has developed standardized requirements for reporting national inventories.

The UNFCCC reporting guidelines on annual inventories require Parties included in Annex I to the Convention (Annex I Parties), by 15 April each year, to provide annual national GHG inventories covering emissions and removals of direct GHGs (CO_2, CH_4, N_2O, HFCs, PFCs and SF_6) from six sectors (Energy, Industrial processes, Solvents, Agriculture, LULUCF, Waste), and for all years from the base year or period to the most recent year.

Under the UNFCCC reporting guidelines for Annex I Parties, inventory submissions are in two parts:

- Common reporting format (CRF) – a series of standardized data tables containing mainly numerical information and submitted electronically
- National Inventory Report (NIR) – a comprehensive description of the methodologies used in compiling the inventory, the data sources, the institutional structures and quality assurance and control procedures

Well-constructed annual inventories should include sufficient documentation and data to enable the reader to understand the underlying assumptions and calculations of the reported emission estimates.

The NIR as established by decision 18/CP.8 is one element of the annual greenhouse gas (GHG) inventory that is required to be submitted to the UNFCCC by Annex I Parties to the Convention. The other elements of this submission include the reporting of GHG emissions by sources and removals by sinks and any other additional information in support of this submission.

Annex I Parties that are also Parties to the Kyoto Protocol are also required to report supplementary information required under Article 7, paragraph 1, of the Kyoto Protocol, with the inventory submission due under the Convention, in accordance with paragraph 3(a) of decision 15/CMP.1.

The review of GHG inventories comprises three stages. Each stage complements the previous one, and ensures that the process as a whole provides a thorough and technical assessment of the inventory and of conformity with the UNFCCC and IPCC guidelines.

- Initial check: immediate quality assurance check to verify that the inventory submission is complete and in the correct format. The result is a status report whose main purpose is to provide a brief check of completeness of the inventory submission, mainly based on the CRF.
- Synthesis and assessment: Part I compile and compare basic inventory information, such as emission trends, activity data and implied emission factors, across Parties and over time. Part II provides a 'preliminary assessment' of the inventory of individual Parties. The identification of potential problems in this assessment is an important input to the individual review stage.
- Individual review: international teams of sectoral inventory experts examine the data, methodologies and procedures used in preparing the national inventory. Reviews are conducted as a centralized review, where 5–8 inventories are reviewed by an expert review team (ERT) convened at the secretariat; a desk review, where 3–5 inventories are reviewed by experts based in their home countries; or an in-country review, where a single inventory is reviewed by an ERT in the Party under review. This is the most important and detailed review stage.

2.3 Kyoto Protocol (KP)

(Source: www.unfccc.int)

The Kyoto Protocol is an international agreement linked to the United Nations Framework Convention on Climate Change, adopted in Kyoto, Japan, on 11 December 1997. The major feature of the Kyoto Protocol is that it sets binding targets for 37 industrialized countries and the European community for reducing greenhouse gas (GHG) emissions. These amount to an average of five per cent against 1990 levels over the five-year period 2008-2012. The major distinction between the Protocol and the Convention is that while the Convention encouraged industrialized countries to stabilize GHG emissions, the Protocol commits them to do so.

Recognizing that developed countries are principally responsible for the current high levels of GHG emissions in the atmosphere as a result of more than 150 years of industrial activity, the Protocol places a heavier burden on developed nations under the principle of "common but differentiated responsibilities."

Pursuant to Article 22, the Protocol is subject to ratification, acceptance, approval or accession by Parties to the UNFCCC. Parties to the UNFCCC that have not signed the Protocol may accede to it at any time.

The Kyoto Protocol sets binding emission reduction targets for 37 industrialized countries and the European community in its first commitment period. Overall, these targets add up to an average five per cent emissions reduction compared to 1990 levels over the five-year period 2008 to 2012. KP was structured on the principles of the Convention. It only binds developed countries because it recognizes that they are largely responsible for the current high levels of GHG emissions in the atmosphere, which are the result of more than 150 years of industrial activity. KP places a heavier burden on developed nations under its central principle: that of "common but differentiated responsibility".

The Protocol entered into force on 16 February 2005 in accordance with Article 23, that is the ninetieth day after the date on which not less than 55 Parties to the UNFCCC, incorporating Parties included in Annex I which accounted in total for at least 55% of the total carbon dioxide emissions for 1990 of the Parties included in Annex I, have deposited their instruments of ratification, acceptance, approval or accession.

Currently, there are 192 Parties (191 States and 1 regional economic integration organization) to the Kyoto Protocol to the UNFCCC. The total percentage of Annex I Parties emissions is 63.7%.

2.3.1 Mechanisms of Kyoto Protocol

(Source: www.unfccc.int)

Countries with commitments under the Kyoto Protocol to limit or reduce greenhouse gas emissions must meet their targets primarily through national measures. As an additional means of meeting these targets, the Kyoto Protocol introduced three market-based mechanisms, thereby creating what is now known as the "carbon market."

The Kyoto mechanisms are:

- Emissions Trading
- The Clean Development Mechanism (CDM)
- Joint Implementation (JI)

Emissions Trading

Parties with commitments under the Kyoto Protocol (Annex B Parties) have accepted targets for limiting or reducing emissions. These targets are expressed as levels of allowed emissions, or "assigned amounts," over the 2008-2012 commitment period. The allowed emissions are divided into "assigned amount units" (AAUs). Emissions trading, as set out in Article 17 of the Kyoto Protocol, allows countries that have emission units to spare - emissions permitted them but not "used" - to sell this excess capacity to countries that are over their targets. Thus, a new commodity was created in the form of emission reductions or removals. Since carbon dioxide is the principal greenhouse gas, people speak simply of trading in carbon. Carbon is now tracked and traded like any other commodity. This is known as the "carbon market."

Clean Development Mechanism (CDM)

The Clean Development Mechanism (CDM), defined in Article 12 of the Protocol, allows a country with an emission-reduction or emission-limitation commitment under the Kyoto Protocol (Annex B Party) to implement an emission-reduction project in developing countries. Such projects can earn saleable certified emission reduction (CER) credits, each equivalent to one tonne of CO_2, which can be counted towards meeting Kyoto targets. The mechanism is seen by many as a trailblazer. It is the first global, environmental investment and credit scheme of its kind, providing a standardized emission offset instrument, CERs. A CDM project activity might involve, for example, a rural electrification project using solar panels or the installation of more energy-efficient boilers. The mechanism stimulates sustainable development and emission reductions, while giving industrialized countries some flexibility in how they meet their emission reduction or limitation targets.

Joint Implementation (JI)

The mechanism known as "joint implementation," defined in Article 6 of the Kyoto Protocol, allows a country with an emission reduction or limitation commitment under the Kyoto Protocol (Annex B Party) to earn emission reduction units (ERUs) from an emission-reduction or emission removal project in another Annex B Party, each equivalent to one tonne of CO_2, which can be counted towards meeting its Kyoto target. Joint implementation offers Parties a flexible and cost-efficient means of fulfilling a part of their Kyoto commitments, while the host Party benefits from foreign investment and technology transfer.

The Kyoto mechanisms:

- Stimulate sustainable development through technology transfer and investment
- Help countries with Kyoto commitments to meet their targets by reducing emissions or removing carbon from the atmosphere in other countries in a cost-effective way
- Encourage the private sector and developing countries to contribute to emission reduction efforts

Accounting, Reporting & Review under the Kyoto Protocol

The Kyoto Protocol's effectiveness will depend upon two critical factors: whether Parties follow the Protocol's rulebook and comply with their commitments; and whether the emissions data used to assess compliance is reliable. Recognizing this, the Kyoto Protocol and Marrakesh Accords, adopted by CMP 1 in Montreal, Canada, in December 2005, include a set of monitoring and compliance procedures to enforce the Protocol's rules, address any compliance problems, and avoid any error in calculating emissions data and accounting for transactions under the three Kyoto mechanisms (emissions trading, clean development mechanism and joint implementation) and activities related to land use, land use change and forestry (LULUCF).

The Protocol's monitoring procedures are based on existing reporting and review procedures under the Convention, building on experience gained in the climate change process over the past decade. They also involve additional accounting procedures that are needed to track and record Parties' holdings and transactions of

Kyoto Protocol units - assigned amount units (AAUs), certified emission reductions (CERs) and emission reduction units (ERUs) - and removal units (RMUs) generated by LULUCF activities.

Articles 5, 7 and 8 of the Kyoto Protocol address reporting and review of information by Annex I Parties under the Protocol, as well as national systems and methodologies for the preparation of greenhouse gas inventories.

- Article 5 commits Annex I Parties to having in place, no later than 2007, national systems for the estimation of greenhouse gas emissions by sources and removals by sinks (Article 5.1). It also states that, where agreed methodologies (that is, the revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories) are not used to estimate emissions and removals, appropriate "adjustments" should be applied (Article 5.2).
- Article 7 requires Annex I Parties to submit annual greenhouse gas inventories, as well as national communications, at regular intervals, both including supplementary information to demonstrate compliance with the Protocol. In addition, Article 7 states that the Conference of the Parties serving as the meeting of the Parties to the Protocol (CMP) shall decide upon modalities for the accounting of assigned amounts prior to the first commitment period.
- Article 8 establishes that expert review teams will review the inventories, and national communications submitted by Annex I Parties.

The Protocol states that guidelines for national systems, adjustments, the preparation of inventories and national communications, as well as for the conduct of expert reviews, should be adopted by the CMP at its first session (CMP 1), and regularly reviewed thereafter.

2.4 European Commission – DG Clima

(Source: http://ec.europa.eu/dgs/clima)

The Directorate-General for Climate Action ("DG CLIMA") was established in February 2010, climate change being previously included in the remit of DG Environment of the European Commission. It leads international negotiations on climate, helps the EU to deal with the consequences of climate change and to meet its targets for 2020, as well as develops and implements the EU Emissions Trading System.

2.5 Combating climate change within and outside the EU

Given the necessity to keep global average temperature increase below 2 degrees Celsius compared to pre-industrial levels, DG CLIMA develops and implements cost effective international and domestic climate change policies and strategies in order for the EU to meet its targets for 2020 and beyond, especially with regard to reducing its greenhouse gas emissions. Its policies also aim at protecting the ozone layer and at ensuring that the climate dimension is appropriately present in all Community policies and that adaptation measures will reduce the European Union's vulnerability to the impacts of climate change.

The Directorate-General for Climate Action is at the forefront of international efforts to combat climate change. It leads the respective Commission task forces on the international negotiations in the areas of climate change and ozone depleting substances and coordinates bi-lateral and multi-lateral partnerships on climate change and energy with third countries.

DG CLIMA develops and implements the EU Emissions Trading System ("EU ETS") and promotes its links with other carbon trading systems with the ultimate aim of building an international carbon trading market. Furthermore, it monitors the implementation of Member States' emission reduction targets in the sectors outside the EU ETS ("Effort Sharing Decision").

It also promotes the development and demonstration of low carbon and adaptation technologies, especially through the development and implementation of cost effective regulatory frameworks for their deployment (e.g. carbon capture and storage, fluorinated gases, ozone depleting substances, vehicle efficiency standards, fuel quality standards) as well as through the development of appropriate financial support schemes.

Combating climate change is a top priority for the EU. Europe is working hard to cut its greenhouse gas emissions substantially while encouraging other nations and regions to do likewise. At the same time, the EU is developing a strategy for adapting to the impacts of climate change that can no longer be prevented. Reining in climate change carries a cost, but doing nothing will be far more expensive in the long run. Moreover, investing in the green technologies that cut emissions will also create jobs and boost the economy.

The European Union has long been a driving force in international negotiations that led to agreement on the two United Nations climate treaties, the UN Framework Convention on Climate Change (UNFCCC) in 1992 and the Kyoto Protocol in 1997.

The Kyoto Protocol requires the 15 countries that were EU members at the time ('EU-15') to reduce their collective emissions in the 2008-2012 period to 8% below 1990 levels. Emissions monitoring and projections show that the EU-15 is well on track to meet this target.

In 2007 EU leaders endorsed an integrated approach to climate and energy policy and committed to transforming Europe into a highly energy-efficient, low carbon economy. They made a unilateral commitment that Europe would cut its emissions by at least 20% of 1990 levels by 2020. This commitment is being implemented through a package of binding legislation.

The EU has also offered to increase its emissions reduction to 30% by 2020, on condition that other major emitting countries in the developed and developing worlds commit to do their fair share under a future global climate agreement. This agreement should take effect at the start of 2013 when the Kyoto Protocol's first commitment period will have expired.

The Cancún Agreement, a balanced and substantive package of decisions adopted at the end of the UN Climate Conference in Mexico (December 2010), represents an important step on the road to building a comprehensive and legally binding framework for climate action for the period after 2012.

The UNFCCC commits the EU and its Member States to develop, periodically update, publish and report to the Conference of the Parties national inventories of anthropogenic emissions by sources and removals by sinks of all greenhouse gases not controlled by the Montreal Protocol on substances that deplete the ozone layer (greenhouse gases), using comparable methodologies agreed upon by the Conference of the Parties.

The UNFCCC commits all Parties to formulate, implement, publish and regularly update national, and where appropriate, regional programmes containing measures to mitigate climate change by addressing anthropogenic emissions by sources and removals by sinks of all greenhouse gases.

2.6 Adoption of the Kyoto Protocol

The Conference of the Parties to the Convention, at its first session, concluded that the commitment by developed countries to aim at returning, individually or jointly, their emissions of carbon dioxide and other greenhouse gases not controlled by the Montreal Protocol to the Convention for the Protection of the Ozone Layer to 1990 levels by the year 2000 was inadequate for achieving the Convention's long-term objective of preventing dangerous anthropogenic interference with the climate system.

The Conference further agreed to begin a process to enable appropriate action to be taken for the period beyond 2000, through the adoption of a protocol or another legal instrument. This process resulted in the adoption on 11 December 1997 of the Kyoto Protocol to the United Nations Framework Convention on Climate Change.

2.7 EU and Member States jointly responsible for the quantified emission reduction commitment

The Kyoto Protocol provides for Parties to fulfill their commitments jointly, acting in the framework of and together with a regional economic integration organization. When the Protocol was signed in New York on 29 April 1998, the EU declared that it and its Member States would fulfill their respective commitments of the Protocol jointly.

In deciding to fulfill their commitments, the EU and the Member States are jointly responsible for the fulfillment by the EU of its quantified emission reduction commitment. Consequently, Member States individually and collectively have the obligation to take all appropriate measures, whether general or particular, to ensure fulfillment of the obligations resulting from action taken by the institutions of the EU, including the EU's quantified emission reduction commitment under the Protocol, to facilitate the achievement of this commitment and to abstain from any measure that could jeopardize the attainment of this commitment.

The Kyoto Protocol requires the EU to reduce greenhouse gas emissions by 8% below 1990 levels by 2008-2012. Most of the Member States that joined the EU in 2004 have the same target. The target for Hungary and Poland is -6% while Cyprus is no Annex-I Party to the UNFCCC and thus has no target.

2.8 EU monitoring and reporting of greenhouse gas emissions under the UNFCC and the Kyoto Protocol

Given the UNFCCC and the Kyoto Protocol requirements, there is a need for thorough monitoring and regular assessment of EU greenhouse gas emissions and the measures taken by the EU and its Member States in the field of climate change policy need to be analyzed in good time. Therefore, it is appropriate for the European Commission to provide for effective cooperation and coordination in relation to the compilation of the EU greenhouse gas inventory, the evaluation of progress, the preparation of reports, as well as review and compliance procedures enabling the EU to comply with its reporting obligations under the Kyoto Protocol, as laid down in the political agreements and legal decisions taken at the seventh Conference of the Parties to the UNFCCC in Marrakech ("the Marrakech Accords").

The European Environment Agency assists the Commission, as appropriate, with monitoring activities, especially in the scope of the EU inventory system, and in the analysis by the Commission of progress towards the fulfillment of the commitments under the UNFCCC and the Kyoto Protocol.

Since the objectives of complying with the EU's commitments under the Kyoto Protocol, in particular the monitoring and reporting requirements laid down therein, cannot, by their very nature, be sufficiently achieved by the Member States and can therefore be better achieved at EU level, the EU may also adopt measures.

2.9 European Climate Change Programme

The European Commission has taken many climate-related initiatives since 1991, when it issued the first Community strategy to limit carbon dioxide (CO_2) emissions and improve energy efficiency. These include: a directive to promote electricity from renewable energy, voluntary commitments by car makers to reduce CO_2 emissions by 25% and proposals on the taxation of energy products.

However, it is clear that action by both Member States and the European Community needs to be reinforced if the EU is to succeed in cutting its greenhouse gas emissions to 8% below 1990 levels by 2008-2012, as required by the Kyoto protocol.

The EU Council of Environment Ministers acknowledged the importance of taking further steps at Community level by asking the Commission to put forward a list of priority actions and policy measures.

The Commission responded in June 2000 by launching the European Climate Change Programme (ECCP). The goal of the ECCP is to identify and develop all the necessary elements of an EU strategy to implement the Kyoto Protocol.

The development of the first ECCP (2000-2004) involved all the relevant groups of stakeholders working together, including representatives from the Commission's different departments (DGs), the Member States, industry and environmental groups. The second European Climate Change Programme (ECCP II) was launched in October 2005.

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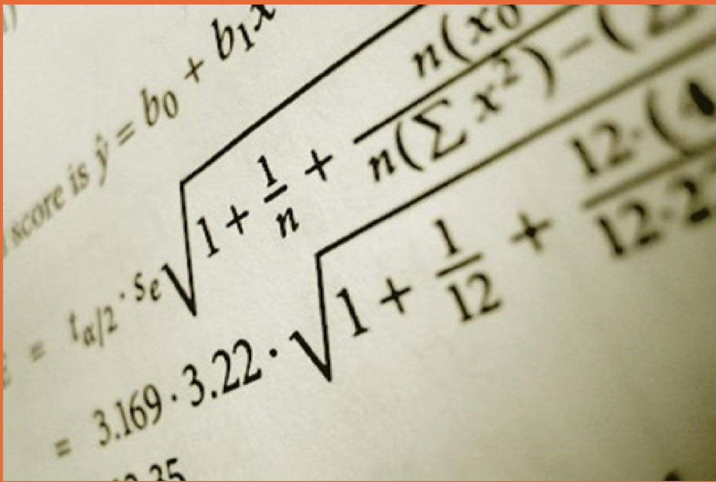
Chapter

10



Advanced Statistics

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Advanced Statistics

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1 Basic Concepts in Statistics

Bill Pelham, used to say about statistics and probability theory: "Figures can't lie, but liars sure can figure." On the second hand Pearson (the father of the correlation coefficient) said "The record of a month's roulette playing at Monte Carlo can afford us material for discussing the foundations of knowledge."

One purpose of this subject is that the students finally prefer Pearson's point of view rather than Pelham's. The purpose of this chapter is to serve as a quick refresher course that will make the rest of this subject more useful. Before going further into a detailed discussion of statistics, we have to remind that (a) statistics is a branch of mathematics and (b) statistics is its own very precise language.

1.1 Definition of Statistics

Statistics is the science that deals with the collection, classification, analysis, and interpretation of numerical facts or data, and that, by use of mathematical theories of probability, imposes order and regularity on aggregates of more or less disparate elements.

Random experiments:

A random experiment is an experiment in which:

- All outcomes of the experiment are known in advance
- Any performance of the experiment results in an outcome that is not known in advance
- And the experiment can be repeated under identical conditions

Sample space:

The sample space of a statistical experiment, Ω, is the set of all possible outcomes of a random experiment. It can be finite, infinite or infinite numerable.

The pair (Ω, **A**) where **A** is the σ-algebra of all the subsets of Ω. Any element of **A** is an event.

The Linear Model:

One of the main methods of applied Statistics is the Linear Model. The linear model involves the simplest and seemingly most restrictive statistical properties: independence, normality, constancy of variance, and linearity. However, the model and the statistical methods associated with it are surprisingly versatile and robust. A deep knowledge of these models makes the use of advanced statistical tools easier. Since most advanced tools are generalizations of the linear model.

http://verde.esalq.usp.br/~jorge/cursos/cesar/Linear%20Models%20in%20Statistics,%20 2nd%20Ed.pdf

1.2 What is a linear model?

A linear model is simply a relationship between one random variable and one or more mathematical variables qualitative or quantitative.

The scientific method is frequently used as a guided approach to learning. Linear statistical methods are widely used as part of this learning process:

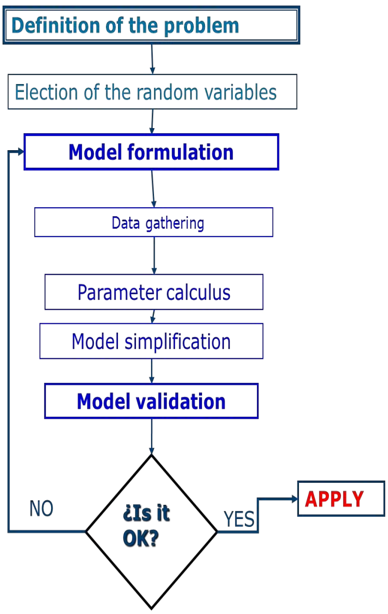


Figure 1. *Modelization Process*

There are two main types of models:

- Experimental design models in which the independent variables are qualitative, and the researcher can control them.

- Regression models in which the independent variables are quantitative and ca not be under control.
- Once the model has been formulated, it will be simplified applying different tests to its parameters.

As an example of its application is:

Let $x_1, x_2, \ldots, x_k$ be k- independent random variables, whose mean is $E[x_i] = \mu_i$, and the constant variance is σ^2. If we took n_i data from each variable, could we accept that the mean for the variable is the same for every level of the factor?

$H_o=\mu_1=\mu_2=...=\mu_k$

This formulation is very frequent in environmental studies: soil behaviour with different chemicals, analysis of pollution filters, machinery performance, etc..

1.3 Definition of a linear model

Let $X=(X_1, X_2,..., X_n)$ be a random vector, let A be a matrix *nxk / k<n* of known constants a_{ij} (values of the independent variables), with *i=1,..n; j=1,...,k.* and let β be a unknown vector of parameters, then the vector $X=(X_1, X_2,..., X_n)$ follows a linear model if it can be formulated as:

$X=\beta A'+\varepsilon$

Where $\varepsilon=(\varepsilon_1,\varepsilon_2,...\varepsilon_n)$ is a vector of random variables unmeasurable and they also fulfill that $E[\varepsilon_i]=0$ (mean is 0), $V(\varepsilon_i)=\sigma^2$, they are independent and follow the Normal distribution.

The model in a matrix way is:

$$(X_1, X_2, ..., X_n) = (\beta_1, \beta_2, ..., \beta_k)\begin{bmatrix} a_{11} & a_{21} & \cdots & a_{n1} \\ a_{12} & a_{22} & \cdots & a_{n2} \\ \cdots & \cdots & \cdots & \cdots \\ a_{1k} & a_{2k} & \cdots & a_{nk} \end{bmatrix} + (\varepsilon_1, \varepsilon_2, \ldots, \varepsilon_n)$$

So:

$$X_1 = \beta_1 a_{11} + ... + \beta_k a_{1k} + \varepsilon_1$$

$$X_2 = \beta_1 a_{21} + ... + \beta_k a_{2k} + \varepsilon_2$$

....

$$X_n = \beta_1 a_{n1} + ... + \beta_k a_{nk} + \varepsilon_n$$

Second definition: Let $X=(X_1, X_2,..., X_n)$ be a random vector, and let A be a matrix *nxk / k<n* of known constants a_j , *i=1,..n; j=1,...,k.* let β be a unknown vector of parameters, the distribution of *X* fulfills the linear model if:

$$E[X] = \beta A'$$

1.4 Parameter calculus

We can apply two methods to estimate the parameters:

1. Least quadratic error. The objective of the method is to minimize the following expression:

$$\min \quad \boldsymbol{\varepsilon}' = (X - \beta A')(X - \beta A')' = \sum \varepsilon_i^2$$

2. Maximum Likelihood method. The likelihood function, in this case, is:

$$f_{\beta,\sigma}(x_1,\ldots,x_n) = \frac{1}{\left(\sqrt{2\pi}\ \sigma\right)^n} \exp\left(-\frac{1}{2\sigma^2}\sum_{i=1}^{n}(x_i - \beta_1 a_{i1} - \ldots - \beta_k a_k)^2\right)$$

1.5 Hypothesis test

This hypothesis is about vector β, to decide whether the model can be simplified or not:

$$H_0 : \beta H' = 0$$

Where *H* is a known matrix with size *rxk* and of rank *r<=k*.

So the hypothesis is:

$$(\beta_1, \beta_2, \ldots, \beta_k)\begin{pmatrix} h_{11} & h_{21} & \cdots & h_{r1} \\ h_{12} & h_{22} & \cdots & h_{r2} \\ \ldots & \ldots & \cdots & \ldots \\ h_{1k} & h_{2k} & \cdots & h_{rk} \end{pmatrix} = (0,0,\ldots,0)$$

So:

$$\beta_1 h_{11} + \beta_2 h_{12} + \ldots + \beta_k h_{1k} = 0$$

$$\beta_1 h_{21} + \beta_2 h_{22} + \ldots + \beta_k h_{2k} = 0$$

…

$$\beta_1 h_{r1} + \beta_2 h_{r2} + \ldots + \beta_k h_{rk} = 0$$

(r equations with r constraints the vector β fulfills under the null hypothesis).

To complete the model in (6.1), we make the following additional assumptions about vector $\varepsilon=(\varepsilon_1,\varepsilon_2,\ldots\varepsilon_n)$:

1. ε_i are independent
2. It follows the Gauss Distribution
3. $var(\varepsilon_i)=\sigma^2$ for all i 1, 2, . . . , n, the variance of ε or x does not depend on the values of A (homoscedasticity, homogeneous variance or constant variance.)
4. -$E[\varepsilon_i] = 0$. This implies that x_i depends only on a_i and that all other variation in x_i is random.

Any of these assumptions may fail to hold with real data. A plot of the data will often reveal departures from assumptions

1.6 Theorem

Let be the model $X=\beta A'+\varepsilon$

where *A* is a known matrix *nxk* of Rank *k<n*, β an unknown vector of parameters, and $\varepsilon=(\varepsilon_1,\varepsilon_2,\ldots\varepsilon_n)$ a vector of random variables no measurable, independent that follow the Normal distribution $N(0,\sigma^2)$. When the value of the maximum-likelihood parameter *F* to test $H_0:\beta H'=0$, where *H* is a matrix *rxk* with rank *r<=k*, $F\geq F_0$ this hypothesis will be rejected for a specific α .

We can demonstrate that *F* is:

$$F = \frac{\left(X-\breve{\beta}_0\ A'\right)\left(X-\breve{\beta}_0\ A'\right)-\left(X-\widehat{\beta}\ A'\right)\left(X-\widehat{\beta}\ A'\right)}{\left(X-\widehat{\beta}\ A'\right)\left(X-\widehat{\beta}\ A'\right)}$$

Where $\hat{\beta}$ is the maximum-likelihood estimator of β and $\hat{\beta}_0$ of β under the null hypothesis.

The random variable *[(n-k)/r]F* follows the F-snedecor distribution with *(r,n-k)* freedom degrees under H_0.

2 Simple Linear Regression

The simple linear regression model for n observations can be written as

$$Y_i = \alpha_0 + \alpha_1 x_i + \varepsilon_i \quad \forall i \in [1,n]$$

The designation simple indicates that there is only one x to predict the response y, and linear means that the model is linear in α_0 α_1. Actually, it is the assumption $E[Y_i] = \alpha_0 + \alpha_1 x_i$ that is linear.

For example, a model such as $Y_i = \alpha_0 + \alpha_1 x_i^2 + \varepsilon_i \quad \forall i \in [1,n]$ is linear in α_0 α_1, whereas the model $Y_i = \alpha_0 + e^{\alpha_1 x_i} + \varepsilon_i \quad \forall i \in [1,n]$ is not linear.

We assume that y_i and ε_i are random variables and that the values of x_i are known constants, which means that the same values of $x=(x_1, x_2, \ldots, x_n)$ would be used in repeated sampling.

We make the following additional assumptions about vector $\varepsilon=(\varepsilon_1,\varepsilon_2,\ldots\varepsilon_n)$:

1. ε_i are independent
2. It follows the Gauss Distribution
3. $var(\varepsilon_i)=\sigma^2$ for all i 1, 2, . . . , n, the variance of ε or y does not depend on the values of X (homoscedasticity, homogeneous variance or constant variance.)
4. -$E[\varepsilon_i] = 0$. This implies that $E[Y_i] = \alpha_0 + \alpha_1 x_i$

If these assumptions are hold, then the least-squares estimators are unbiased and have minimum variance among all linear unbiased estimators.

2.1 The Process

1. Graphical Representation of the data.
2. Estimation of the parameters.
3. Hypothesis test and confidence intervals.
4. Test of the residual assumptions.

For example, in a plant of oxygen production, the scientists want to check if the quality of the produced oxygen depends on the percentage of hydrocarbon in the main capacitor in the process unit.

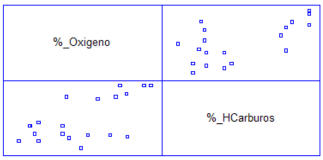


Figure 2. Graphic of the data of the variables oxygen and hydrocarbon

2.2 Estimation of the parameters: α_0, α_1, σ^2.

We will apply the maximum likelihood method to determine the expression of the estimators of the regression parameters that make the probability of obtaining the sample maximum.

The likelihood function for the parameters α_0 α_1 σ^2 is:

$$f(X, \alpha_0, \alpha_1, \sigma^2) = \frac{1}{(2\pi)^{n/2}\sigma^n} e^{-\frac{1}{2\sigma^2}\sum_{i=1}^{n}(y_i - \alpha_0 - \alpha_1 x_i)^2}$$

The values of α_0 α_1 σ^2 are obtained from:

$$\frac{\partial f}{\partial \alpha_0} = 0; \ \frac{\partial f}{\partial \alpha_1} = 0; \ \frac{\partial f}{\partial \sigma^2} = 0$$

The estimators are the following, after processing the equations above:

$$\hat{\alpha}_0 = \sum_{i=1}^{n} \frac{Y_i}{n} - \hat{\alpha}_i \overline{x} = \overline{Y} - \hat{\alpha}_i \overline{x}$$

$$\hat{\alpha}_1 = \frac{\sum_{i=1}^{n} (y_i - \overline{y})(x_i - \overline{x})}{\sum_{i=1}^{n} (x_i - \overline{x})^2} = \frac{Cov(y,x)}{\sigma^2_x}$$

The regression model for the *i- component* of vector Y is

$$\hat{Y}_i = \overline{Y} + \hat{\alpha}_1 (x_i - \overline{x})$$

Where $\overline{x} = \sum_{i=1}^{n} \frac{x_i}{n}$

The estimation of the variance is the following:

$$\hat{\sigma}^2 = \frac{1}{n} \sum_{i=1}^{n} (y_i - \hat{\alpha}_0 - \hat{\alpha}_1 x_i)^2 = \frac{1}{n} \sum e_i^2$$

On the second hand, the value of the residual e_i or error of the model is:

$e_i = y_i - \hat{\alpha}_0 - \hat{\alpha}_1 x_i$ That is the difference between the actual value and the estimated one:

So $\hat{\sigma}^2 = 1/n \sum_{i=1}^{n} e_i^2$ is the quadratic mean of the residuals.

But the *n-residuals* do not are all independent. They must fulfill two constraints that appear in the process of the maximum likelihood method:

$$\sum e_i = 0$$

$$\sum e_i x_i = 0$$

So the number of freedom degrees is n-2. The estimator of the variance will be:

$$\hat{S}_R^{\,2} = \frac{1}{n-2}\sum_{i=1}^{n} e_i^{\,2}$$

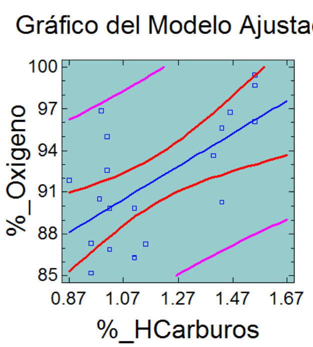
These estimators have the following properties:

- Independence
- Normality
- Homocedasticity

```
Análisis de Regresión - Modelo Lineal Y = a + b*X
-----------------------------------------------------------------------------
Variable dependiente: %_Oxigeno
Variable independiente: %_HCarburos
-----------------------------------------------------------------------------
                                 Error         Estadístico
Parámetro      Estimación       estándar           T              P-Valor
-----------------------------------------------------------------------------
Ordenada         77.8633         4.19889        18.5438           0.0000
Pendiente         11.801         3.48512        3.38612           0.0033
-----------------------------------------------------------------------------
 Estimation α0           Estimation α1
                              Análisis de la Varianza
-----------------------------------------------------------------------------
Fuente            Suma de cuadrados     GL  Cuadrado medio Cociente-F   P-Valor
-----------------------------------------------------------------------------
Modelo                     148.313       1        148.313      11.47     0.0033
Residuo                    232.834      18        12.9352
-----------------------------------------------------------------------------
Total (Corr.)              381.147      19

Coeficiente de Correlación = 0.623797
R-cuadrado = 38.9122 porcentaje
R-cuadrado (ajustado para g.l.) = 35.5185 porcentaje
Error estándar de est. = 3.59656
Error absoluto medio = 2.84593
Estadístico de Durbin-Watson = 1.91084 (P=0.3683)
Autocorrelación residual en Lag 1 = 0.0226275
```

Figure 3. Statgraphics output of a regression model which includes the value of the estimators



% Oxigeno = 77.8633 + 11.801*% HCarburos

Figure 4. Graphic of the linear regression model between variables hydrocarbon and oxygen and the confidence intervals for the data and the mean values.

2.3 Simplification tests

The following step tests weather the model can be simplified or not.

1- The first test checks if the model is linear:

H_0: α_1=0

This expression according to the formulation of the general linear model is:

$$H_0 : \beta H' = 0 \qquad\qquad (\alpha_0\ \alpha_1)\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = 0$$

The simplest expression of matrix H is:

H=(0,1).

Statistic F:

Under the null hypothesis, that is, when $\alpha_1 = 0$, the estimators are:

$$\hat{\alpha}_{00} = \overline{Y}\ ;\ \hat{\alpha}_{10} = 0\ ;\ \hat{\sigma}^2{}_0 = \frac{1}{n}\sum_{i=1}^{n}(Y_i - \overline{Y})^2$$

So the estimator *F* is:

$$F = \frac{\sum_{i=1}^{n}(Y_i - \overline{Y})^2 - \sum_{i=1}^{n}(Y_i - \overline{Y} + \hat{\alpha}_1\overline{X} - \hat{\alpha}_1 X_i)^2}{\sum_{i=1}^{n}(Y_i - \overline{Y} + \hat{\alpha}_1\overline{X} - \hat{\alpha}_1 a X_i)^2} = \frac{\hat{\alpha}_1{}^2\sum_{i=1}^{n}(X_i - \overline{X})^2}{\sum_{i=1}^{n}(Y_i - \overline{Y} + \hat{\alpha}_1\overline{X} - \hat{\alpha}_1 X_i)^2}$$

The statistic *(n-2)/1 F* follows the distribution F-sneadecor with *(1, n-2)* degrees of freedom, which is the square of the t-student distribution with *(n-2)* degrees of freedom.

If *(n-2)F>C* then the hypothesis is rejected. In the case of the t-student distribution, the null hypothesis is rejected when:

$$\sqrt{F} = |\hat{\alpha}_1| \sqrt{\frac{(n-2)\sum_{i=1}^{n}(X_i - \overline{X})^2}{\sum_{i=1}(Y_i - \overline{Y} + \hat{\alpha}_1 \overline{X} - \hat{\alpha}_1 X_i)^2}} > C'$$

Where C' is the value of the t-student distribution for a specific degrees of freedom and confidence level.

2- The second simplification tests is to check if the constant is null. α_o*=0*

The hypothesis is:

$H_o:\alpha_o=0$

This expression according to the formulation of the general linear model is:

$$H_0 : \beta H' = 0 \qquad (\alpha_0\ \alpha_1)\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = 0$$

The simplest expression of matrix H is:

H=(0,1).

Statistic F:

Under the null hypothesis, that is, when $\alpha_1 = 0$, the estimators are:

$$(\hat{\alpha}_0)_0 = 0;\ (\hat{\alpha}_1)_0 = \frac{\sum_{i=1}^{n} X_i Y_i}{\sum_{i=1}^{n} X_i^2};\ \hat{\sigma}^2{}_0 = \frac{1}{n}\sum_{i=1}^{n}(Y_i - \hat{\alpha}_i X_i)^2$$

So the statistic *F* is:

$$F=\frac{\sum_{i=1}^{n}(Y_i-(\hat{\alpha}_1)_0 X_i)^2-\sum_{i=1}^{n}(Y_i-\overline{Y}+\hat{\alpha}_1\overline{X}-\hat{\alpha}_1 X_i)^2}{\sum_{i=1}^{n}(Y_i-\overline{Y}+\hat{\alpha}_1\overline{X}-\hat{\alpha}_1 X_i)^2}$$

The statistic *(n-2)/1 F* follows the distribution F-sneadecor with *(1, n-2)* degrees of freedom, which is the square of the t-student distribution with *(n-2)* degrees of freedom.

$(\hat{\alpha}_1)_0$ can be expressed in function of $\hat{\alpha}_1$:

$$(\hat{\alpha}_1)_0=\hat{\alpha}_1+\frac{n\hat{\alpha}_0\overline{X}}{\sum_{i=1}^{n}X_i^2}$$

As a result, *F* is:

$$F=\frac{\hat{\alpha}_0^2\, n\sum_{i=1}^{n}(X_i-\overline{X})^2/\sum_{i=1}^{n}X_i^2}{\sum_{i=1}^{n}(Y_i-\overline{Y}+\hat{\alpha}_1\overline{X}-\hat{\alpha}_1 X_i)^2}$$

If *(n-2)F>C* then the hypothesis is rejected. In the case of the t-student distribution, the null hypothesis is rejected when:

$$\sqrt{F}=|\hat{\alpha}_0|\sqrt{\frac{n(n-2)\sum_{i=1}^{n}(X_i-\overline{X})^2/\sum_{i=1}^{n}X_i^2}{\sum_{i=1}^{n}(Y_i-\hat{\alpha}_0-\hat{\alpha}_1 X_i)^2}}>C'$$

Where *C'* is the value of the t-student distribution for specific degrees of freedom and Confidence level.

3- Finally, we can test if $H_0:\alpha_0=0;\alpha_1=0$ *are both zero.*

This expression according to the formulation of the general linear model is:

The simplest expression of matrix H is:

$$\mathrm{H} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$ Statistic F:

Under the null hypothesis, that is, when $\alpha_0 = 0$, $\alpha_1 = 0$, the estimators are:

$$(\hat{\alpha}_0)_0 = 0;\ (\hat{\alpha}_1)_0 = 0;\ (\hat{\sigma}^2)_0 = \frac{1}{n}\sum_{i=1}^{n} Y_i^2$$

AS a result, *F* is:

$$F = \frac{n\sum_{i=1}^{n}(\hat{\alpha}_0 - \hat{\alpha}_1\overline{X})^2 + \hat{\alpha}_1^2\sum_{i=1}^{n}(X_i - \overline{X})^2}{\sum_{i=1}^{n}(Y_i - \hat{\alpha}_0 + \hat{\alpha}_1 X_i)^2}$$

If *(n-2)F>C* then the hypothesis is rejected.

Confidence intervals for parameters α_0, α_1:

Let $1-\alpha$, the level of confidence, the interval for parameter α_0 is:

$$\left(\hat{\alpha}_0 - t_{n-2,\alpha/2}\sqrt{\frac{\sum_{i=1}^{n}(Y_i - \hat{\alpha}_0 - \hat{\alpha}_1 X_i)^2 \sum_{i=1}^{n} X_i^2}{n(n-2)\sum_{i=1}^{n}\left(X_i - \overline{X}\right)^2}}\ ;\ \hat{\alpha}_0 + t_{n-2,\alpha/2}\sqrt{\frac{\sum_{i=1}^{n}(x_i - \hat{\alpha}_0 - \hat{\alpha}_1 X_i)^2 \sum_{i=1}^{n} X_i^2}{n(n-2)\sum_{i=1}^{n}\left(X_i - \overline{X}\right)^2}} \right)$$

And for α_1 is:

$$\left(\hat{\alpha}_1 - t_{n-2,\alpha/2}\sqrt{\frac{\sum_{i=1}^{n}\left(Y_i - \hat{\alpha}_0 - \hat{\alpha}_1 X_i\right)^2}{(n-2)\sum_{i=1}^{n}\left(X_i - \overline{X}\right)^2}}\ ;\ \hat{\alpha}_1 + t_{n-2,\alpha/2}\sqrt{\frac{\sum_{i=1}^{n}\left(Y_i - \hat{\alpha}_0 - \hat{\alpha}_1 Y_i\right)^2}{(n-2)\sum_{i=1}^{n}\left(Y_i - \overline{Y}\right)^2}} \right)$$

2.4 Correlation coefficient

The correlation coefficient measures the linear relationship between two variables.

$$\rho = \frac{cov(Y,X)}{S_X S_X}$$

If the value of this coefficient is 1 or -1 the linear dependence is complete between the two variables.

3 Hypothesis tests of the correlation coefficient

1 H_0: ρ=0 and H_1: ρ≠0

In this case, the statistic is $t = \sqrt{n-2}\,\frac{r}{\sqrt{1-r^2}}$. It follows the Student distribution with (n-2) degrees of freedom.

2 H_0: ρ=ρ_0 ≠0 frente a H_1: ρ≠ρ_0

$z = \frac{1}{2}\ln\left(\frac{1+r}{1-r}\right)$ is the statistic used in this test. It follows the Gauss distribution with the following parameters.

$$E(z) = \frac{1}{2}\ln\left(\frac{1+\rho_0}{1-\rho_0}\right) + \frac{\rho_0}{2(n-1)} \qquad \mathrm{var}(z) = \frac{1}{n-3}$$

3.1 Analysis of the residuals

Normality hypothesis

- Non-parametric tests of goodness of fitting:
  - **Normal probability plot-**

The normal probability plot is a graphical technique for normality testing: assessing whether or not a data set is approximately normally distributed.

The data are plotted against a theoretical normal distribution in such a way that the points should form an approximate straight line. Departures from this straight line indicate departures from normality

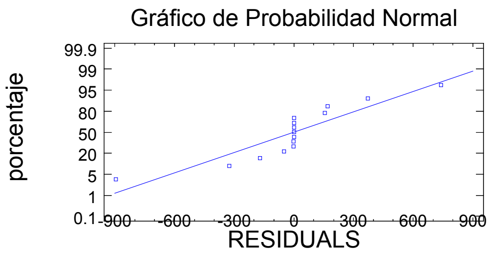


Figure 5. Shows a case in which the variable does not follow the normal distribution.

- **Shapiro-Wilk test**

In Statistics, the Shapiro–Wilk test tests the null hypothesis that a sample x_1, ..., x_n came from a normally distributed population. It was published in 1965 by Samuel Shapiro and Martin Wilk. The statistic of the test is:

$$W = \frac{\left(\sum_{i=1}^{n/2} a_{n-1} \left(u_{n-i+1} - u_i \right) \right)^2}{\sum_{i=1}^{n} \left(u_i - \bar{u} \right)^2}$$

Where a_i is tabulated and u_i, is the sample ranked.

The critical region of a test is:

$$\mathrm{P}\left(\mathrm{W} \leq \mathrm{K}/\mathrm{H}_0\right) = \text{á}$$

Where K is tabulated.

- **Pearson's chi-squared test:**

It tests a null hypothesis stating that the frequency distribution of certain events observed in a sample is consistent with a particular theoretical distribution. The events considered must be mutually exclusive and have total probability..

The value of the test-statistic is

$$\chi^2 = \sum_{i=1}^{n} \frac{(O_i - E_i)^2}{E_i}$$

where

χ^2 = Pearson's cumulative test statistic, which asymptotically approaches a χ^2 distribution.

O_i= an observed frequency;

E_i= an expected (theoretical) frequency, asserted by the null hypothesis;

n= the number of cells in the table.

The chi-squared statistic can then be used to calculate a p-value by comparing the value of the statistic to a chi-squared distribution. The number of degrees of freedom is equal to the number of cells n, minus the reduction in degrees of freedom, p.

- **Kolmogorov-Smirnov test**

The Kolmogorov–Smirnov test (K–S test) is a nonparametric test for the equality of continuous, one-dimensional probability distributions that can be used to compare a sample with a reference probability distribution (one-sample K–S test), or to compare two samples (two-sample K–S test). The Kolmogorov–Smirnov statistic quantifies a distance between the empirical distribution function of the sample and the cumulative distribution function of the reference distribution, or between the empirical distribution functions of two samples. The null distribution of this statistic is calculated under the null hypothesis that the samples are drawn from the same distribution (in the two-sample case) or that the sample is drawn from the reference distribution (in the one-sample case). In each case, the distributions considered under the null hypothesis are continuous distributions but are otherwise unrestricted. In the special case of testing for normality of the distribution, samples are standardized and compared with a standard normal distribution. This is equivalent to setting the mean and variance of the reference distribution equal to the sample estimates, and it is known that using these to define the specific reference distribution changes the null distribution of the test statistic: see below. Various studies have found that, even in this corrected form, the test is less powerful for testing normality than the Shapiro–Wilks test or Anderson–Darling test, (Stephens, 1974).

The empirical distribution function F_n for n iid observations X_i is defined as

$$F_n(x) = \frac{1}{n}\sum_{i=1}^{n} I_{X_i \leq x}$$

where $I_{X_i \leq x}$ is the indicator function, equal to 1 if $X_i \leq x$ and equal to 0 otherwise.

The Kolmogorov–Smirnov statistic for a given cumulative distribution function F(x) is

$$D_n = \sup_x |F_n(x) - F(x)|$$

where $\sup_x$ is the supremum of the set of distances. By the Glivenko–Cantelli theorem, if the sample comes from distribution F(x), then D_n converges to 0 almost surely.

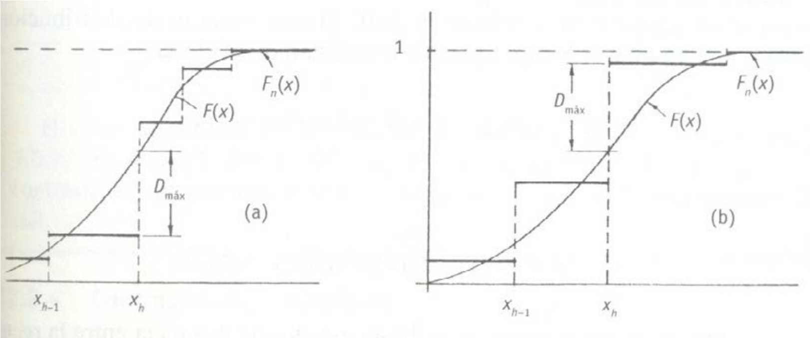


Figure 6. Shows graphically the value of the statistic Dn.

3.2 Independence hypothesis

When the residuals follow a pattern, it can be easily to detect through their graphical representation. This means that the residuals are not independent.

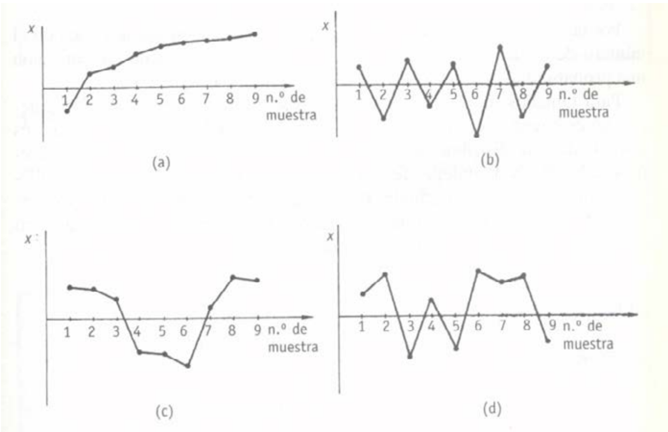


Figure 7. Graphical representation of the residuals

Two of the most applied tests are:

- Autocorrelation coefficient:

  This coefficient measures the linear relationship between every data and that one separated k position in the same sample.

$$r(k) = \frac{\sum_{i=k+1}^{n} (x_i - \bar{x})(x_{i-k} - \bar{x})}{\sum_{i=1}^{n} (x_i - \bar{x})^2}$$

  Where *k* is the lag

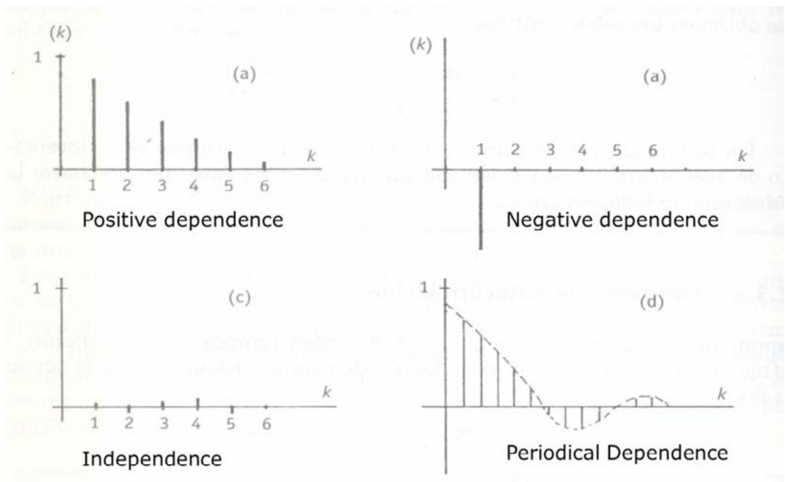


Figure 8. autocorrelograms for different types of dependence of the residuals.

- Durbin-Watson test

  The statistic in this case is:

$$D = \frac{\sum_{i=2}^{n} (e_i - e_{i-1})^2}{\sum_{i=1}^{n} e_i^2}$$

Where e_i are the residuals

If D=0 there is a positive dependence in the residuals.

If D=2 the residuals are independent.

If D=4 there is a negative dependence in the residuals

3.3 Homocedasticity test

There are some tests that allow the tests of this assumption apart from the graphical test. This tests are the Bartlett test, the C of Cochran test, the Harley test and the Levene test. The conditions under these tests can be applied are:

Table 1. Requirements to apply the homocedasticity tests

Test	Normality assumption	Sample size / groups
Bartlett	Yes	Anyone
Cochran	Anyone	Equal
Hartley	Yes	Equal
Levene	Anyone	Anyone

4 Model Evaluation

There are several ways to validate a regression model. This chapter focuses on:

- Analysis of variance
- Lack of fit test
- Identification of outlier residuals
- Identification of influential points

4.1 Analysis of variance

We can break the variability of the variable into components:

$$\sum_{i=1}^{n}(y_i - \bar{y})^2 = \sum_{i=1}^{n}(y_i - \hat{y}_i)^2 + \sum_{i=1}^{n}(\hat{y}_i - \bar{y})^2$$

So the Total Sum of Squares is the Regression Sum of Squares + Error (or Residual) Sum of Squares

We can organize the results of a simple linear regression analysis in an ANOVA table, see figures xxx and xxx.

Source	D.F.	Sum of Squares	Mean Square	F	P-value	
Regression	df_{REG}	$SSREG$	$MSREG$	$\frac{MSREG}{MSE}$	$P(T^2 \geq \frac{MSREG}{MSE})$	$T^2 \sim F(df_{REG}, df_E)$
Error	df_E	SSE	MSE			
Total	df_{TO}	$SSTO$				

Figure 9. ANOVA table of a simple regression model

Source	D.F.	Sum of Squares	Mean Square	F	P-value
Regression	1	$\sum_{i=1}^{n}(\hat{Y}_i - \bar{Y})^2$	$\frac{\sum_{i=1}^{n}(\hat{Y}_i - \bar{Y})^2}{1}$	$\frac{MSREG}{MSE}$	$P(T^2 \geq \frac{MSREG}{MSE})$
Error	$n-2$	$\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2$	$\frac{\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2}{n-2}$		

Figure 10. ANOVA table with the variables and the statistics

The statistic F is used to test the hypothesis:

H_o: E[Y/X]= α_0 versus H_1: E[Y/X]= $\alpha_0 + \alpha_1 X$

Or H_o: $\alpha_1 = 0$ vs H_1: $\alpha_1 \neq 0$ for short

4.2 Lack of fit test

This is an *F* test for checking whether a linear regression function is inadequate in describing the trend in the data:

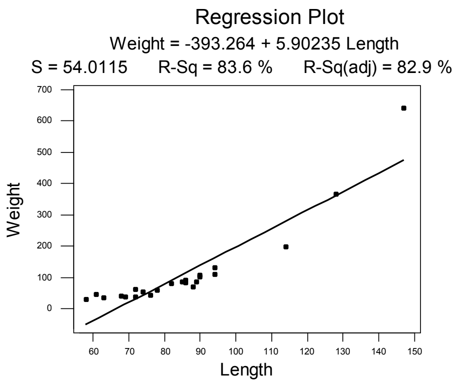


Figure 11. F test for checking whether a linear regression function is inadequate in describing the trend in the data

Do the data suggest that a linear function is inadequate in describing the relationship between the length and weight of an alligator?

Applying a simpler example we are going to show how to detect de lack of fit.Figure 12 shows the notation we are going to apply in this process.

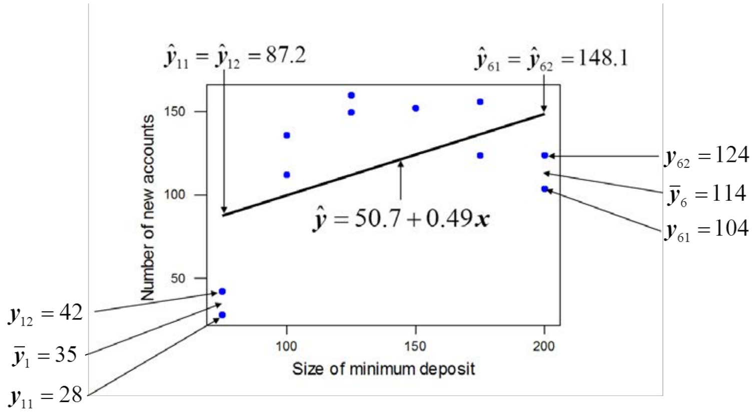


Figure 12. Notation in the lack of fit test

The error variability can be decomposed into two components:

$$\sum_{i=1}^{m}\sum_{j=1}^{n_i}\left(y_{ij} - \hat{y}_i\right)^2 = \sum_{i=1}^{m}\sum_{j=1}^{n_i}\left(y_j - \bar{y}_i\right)^2 + \sum_{i=1}^{m}\sum_{j=1}^{n_i}\left(\bar{y}_i - \hat{y}_i\right)^2$$

$$SSE = SSLF + SSPE$$

On the left the pure error, on the right the lack of fit error, which means that for the same value of X, why the mean value of the actual data If the lack of fit sum of squares is a large component of the residual error, it suggests that a linear function is inadequate.

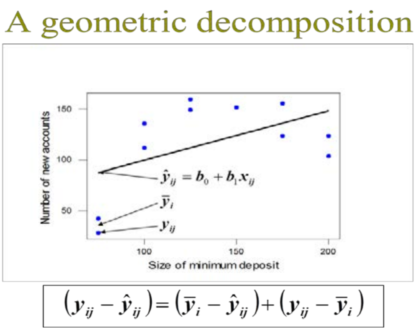


Figure 13. The error variability can be decomposed into two components. On the left the pure error, on the right the lack of fit error.

The degrees of freedom are, SSE has n-2, SSLF has m-2 and SSPE m-c

So the expanded Analysis of Variance is:

Analysis of Variance Table

Source	DF	SS	MS	F
Regression	*1*	$SSR=\sum_{i=1}^{m}\sum_{j=1}^{n_i}(\hat{y}_{ij}-\bar{y})^2$	$MSR=\dfrac{SSR}{1}$	$F=\dfrac{MSR}{MSE}$
Residual error	*n-2*	$SSE=\sum_{i=1}^{m}\sum_{j=1}^{n_i}(y_{ij}-\hat{y}_{ij})^2$	$MSE=\dfrac{SSE}{n-2}$	
Lack of fit	*m-2*	$SSLF=\sum_{i=1}^{m}\sum_{j=1}^{n_i}(\bar{y}_i-\hat{y}_{ij})^2$	$MSLF=\dfrac{SSLF}{m-2}$	$F=\dfrac{MSLF}{MSPE}$
Pure error	*n-m*	$SSPE=\sum_{i=1}^{m}\sum_{j=1}^{n_i}(y_{ij}-\bar{y}_i)^2$	$MSPE=\dfrac{SSPE}{n-m}$	
Total	*n-1*	$SSTO=\sum_{i=1}^{m}\sum_{j=1}^{n_i}(y_{ij}-\bar{y})^2$		

Null hypothesis $H_o: \mu_i = \alpha_o + \alpha_1 X_i$

Alternative hypothesis $H_A: \mu_i \neq \alpha_o + \alpha_1 X_i$

$$F^* = \frac{MSLF}{MSPE}$$

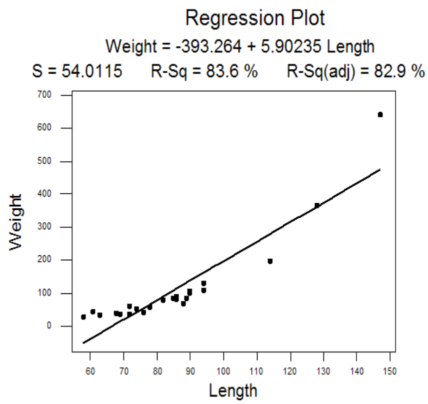


Figure 14. Example of the study of the alligator

Do the data suggest that a linear function is not adequate in describing the relationship between the length and weight of an alligator?

```
Analysis of Variance

Source            DF     SS      MS       F      P
Regression         1  342350  342350  117.35  0.000
Residual Error    23   67096    2917
  Lack of Fit     17   66567    3916   44.36  0.000
  Pure Error       6     530      88
Total             24  409446

14 rows with no replicates
```

So we have to reject the null hypothesis, there is a lack of linearity.

It is okay to perform the LOF Test, when:

- When the "INE" part of the "LINE" assumptions are met.
- The LOF test requires repeat observations, called **replicates**, for <u>at least one</u> of the values of the predictor *X*.

4.3 Identification of Outliers

- The outliers are observations with large (in absolute value) *residuals*.
- Observations falling f a r from the regression line while not following the pattern of the *relationship* apparent in the others
- No son representativos del resto de datos.

We can apply the method of Stefansky (1971) to identify the residuals

$$\frac{|e_i|}{\sqrt{\sum e_i^2}} \geq 2$$

- The origin of these residuals may be because:

1. Wrong measures 2. Wrong analysis 3. Errors in their recording	They are removed
1. Feasible extraordinary observation	They are kept. They may explain especial properties of the model.

In the example of concentration of oxygen and hydrocarbon, there only is one extreme residual, which appears in figure 16:

Residuos Atípicos

Fila	X	Y	Y Predicha	Residuo	Residuo Estudentizado
18	0.99	96.85	89.5463	7.3037	2.38

Figure 15. Example of non-typical residuals of concentration of oxygen and hydrocarbon

The value of the studentized residual is larger than 2, 2.38-

Influential points:

- Points whose removal would greatly affect the association of two variables
- Points whose removal would significantly change the slope of an LSR line
- Points with a large moment (i.e they are far away from the rest of the data.)
- Usually outliers in the x direction

Usually influential points have two characteristics:

They are outliers, i.e. graphically they are far from the pattern described by the other points, that means that the relationship between x and y is different for that point than for the other points.

- They are in a position of high leverage, meaning that the value of the variable x is far from the mean $\bar{x}$. Observations with very low or very high values of x are in positions of high leverage.

The leverage points are detected from the following expression which measures the influence of the extreme point in the regression coefficients.

$$\hat{y} = X\hat{\beta} = X(X'X)^{-1}X'y = Hy$$

The diagonal of matrix H is a measure of the distance between the observation i to the center of the space of X. There is leverage if this value if larger tan:

- $$2\sum_{i=1}^{n} h_{ii} / n$$

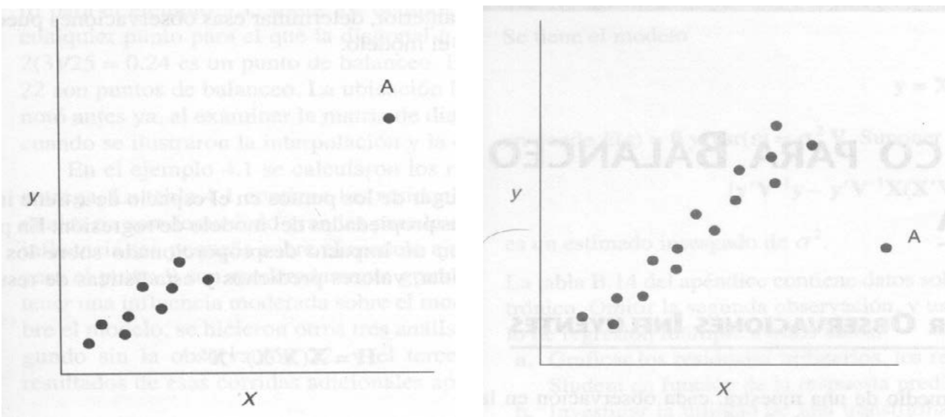


Figure 16. Different graphs of influential points. On the left a leverage point, on the right an influential point

4.4 DFFITS

This method analyzes the influence of the observation i in the prediction.

$$\text{DFFITS}_i = \frac{\hat{y}_i - \hat{y}_{(i)}}{\sqrt{S_{(i)}^2 h_i}} \quad i = 1....n$$

$\hat{y}_{(i)}$ is the adjusted value of y_i when we do not use the observation i

A point is analyzed if:

$$|\text{DFFITS}_i| > 2\sqrt{\sum h_i / n}$$

In figure 18, the two graphs show the same data – the one on the right with the removal of the green data point. As you can see, the removal of this point significantly affects the slope of the regression line. This is an influential point!

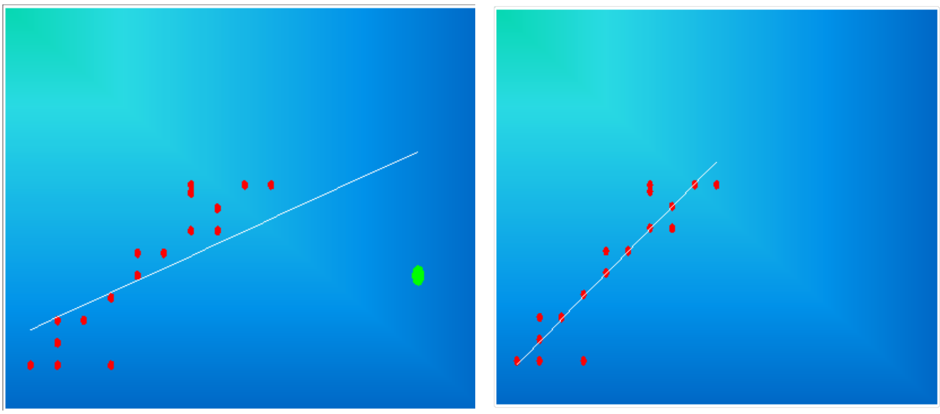
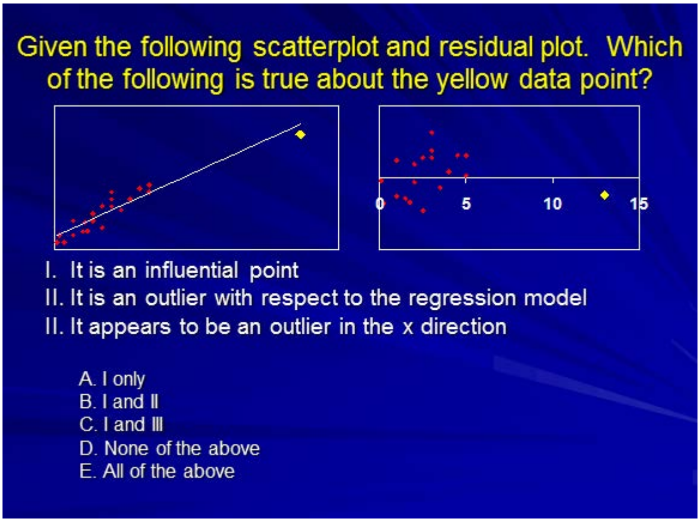


Figure 17. Effect of the influential point in the regression model

Another example:



The correct answer is C

Because this point has a large moment and is far from the rest of the data, it is an influential point. If this point was removed, the slope of the line would markedly change.

II. This point is not an outlier with respect to the model because as you can see in the residual plot, it does not have a large residual (It follows the regression pattern of the data).

III. By looking at both the scatterplot and the residual plot, you can see that the yellow point is an outlier in the x direction (far right of the rest of the data).

5 Transformation of a random variable

When the model does not fits the assumptions of the residuals, some transformations can take place depending on the relation between the variance and the moment of Y.

Table 2. Transformations of variable Y

Relation between σ^2 and E[y]	Transformation
$\sigma^2 \sim$ Constant	$y' = y$
$\sigma^2 \sim E[y]$	$y' = y^{1/2}$
$\sigma^2 \sim E[y]\,[1-E[y]]$	$y' = 1/\mathrm{sen}(y^{1/2})$,
$\sigma^2 \sim E[y]^2$	$Y' = \ln(y)$
$\sigma^2 \sim E[y]^3$	$Y' = y^{-1/2}$
$\sigma^2 \sim E[y]^4$	$Y' = y^{-1}$

5.1 Application of the model

Two intervals of confidence can be calculated, One for the prediction and the second for the moment of Y:

For the prediction:

$$y_0 \in \left(\hat{y}_0 \pm t_{á/2,n-2} \sqrt{S_{res}{}^2 + \frac{S_{res}{}^2}{n} + S_{res}{}^2 \frac{(x_0 - \overline{x})^2}{S_x}} \right).$$

For the moment of Y:

$$E(y/x_0) \in \left(\hat{\imath}_{y|x_0} \pm t_{á/2,n-2} \sqrt{\frac{S_{res}{}^2}{n} + S_{res}{}^2 \frac{(x_0 - \overline{x})^2}{S_x}} \right)$$

The following figure shows graphically both intervals:

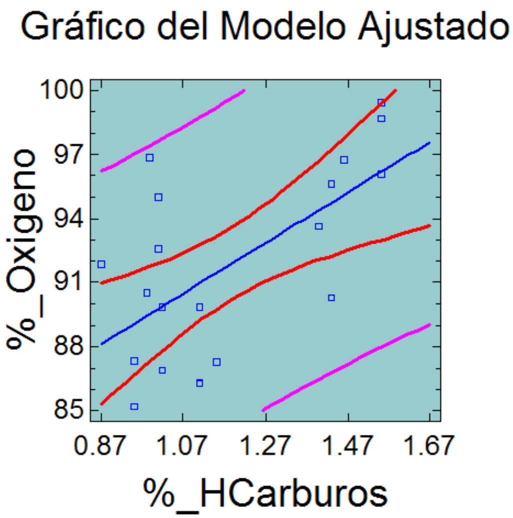


Figure 18. in red the interval for the average of Y, in pink the interval for the prediction.

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CLIMATE CHANGE AND RESTORATION OF DEGRADED LAND

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