The terrestrial carbon cycle on the regional and global scale

Modeling, uncertainties and policy relevance

Jelle Gerlof van Minnen

Promotor:
Prof. Dr. R. Leemans, hoogleraar Milieusysteemanalyse, Wageningen Universiteit

Co-promotor:
Dr. R. Swart, Senior onderzoeker, Milieu en Natuurplanbureau, Bilthoven

Promotiecommissie:
Prof. Dr. W.P. Cramer, Potsdam Institute for Climate Impact Research, Potsdam, Germany
Prof. Dr. Ir. J. Goudriaan, Wageningen Universiteit
Prof. Dr. Ir. G.M.J. Mohren, Wageningen Universiteit
Prof. Dr. Ir. A. Veldkamp, Wageningen Universiteit

The terrestrial carbon cycle on the regional and global scale

Modeling, uncertainties and policy relevance

Jelle Gerlof van Minnen

Proefschrift
ter verkrijging van de graad van doctor
op gezag van de rector magnificus
van Wageningen Universiteit
Prof. Dr. M.J. Kropff
In het openbaar te verdedigen
Op vrijdag 18 januari 2008
Des namiddags te half twee in de aula

Van Minnen, J.G., 2008
The terrestrial carbon cycle on the regional and global scale. Modeling, uncertainties and policy relevance

PhD thesis Wageningen University, with summaries in English and Dutch

ISBN 978-90-8504-810-7

Abstract

In this thesis the IMAGE-2 terrestrial C-cycle model has been used to assess different aspects of the *response of the terrestrial biosphere to changing environmental conditions and land use, and the consequences for the global and regional C cycle*. Developing a more robust understanding of this response and its consequences is needed to define the required long-term emission reductions of greenhouse gases, with the aim of keeping climate change and its impacts at manageable levels. This understanding includes both the underlying processes and their interactions.

The IMAGE-2 terrestrial C-cycle model is described here, with results shown for the different applications under multiple socio-economic and environmental conditions. The position of the IMAGE-2 C-cycle model is also discussed in a broader context by comparing the model's results with observed trends, and comparing the model's algorithm and results with other types of C-cycle models.

On the basis of the analysis presented in this thesis I can conclude that:

- The dynamics in the terrestrial biosphere play a critical role in determining the C cycle, the atmospheric CO_2 concentrations and thus the global climate on time scales ranging from months/seasons to centuries.
- Both natural processes and land use determine the C dynamics in the terrestrial biosphere. The importance of the different processes varies over time and geographical space. This creates a need for an integrated and geographically explicit approach for accurately determining the behavior of the future C cycle as a consequence of changes in energy use, land use and environmental change.
- The terrestrial biosphere can play an important role in "stabilizing the greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." This important role has received insufficient attention in mitigation studies. However, given the importance of the energy sector, solely focusing in climate policies on slowing down deforestation or enhancing afforestation will not be sufficient for mitigating climate change.
- Different uncertainties in the biosphere – the future terrestrial sink, the role of land use, and the sequestration potential of C plantations – have large consequences for the C cycle. This can have considerable consequences for policy measures needed to achieve greenhouse gas stabilization. Reducing some of these uncertainties by developing robust parameterizations should be a key issue in climate change research.
- The IMAGE-2 C-cycle model is an appropriate model for simulating the global and continental dynamics of the terrestrial C cycle on time scales of decades to centuries.

Keywords

C cycle; biosphere; global change; land use; climate change; integrated assessment modeling

Table of Contents

Abstract ***V***
Keywords ***V***

1. Introduction ***1***
- 1.1 Setting the scene *3*
- 1.2 The problem statement *4*
- 1.3 Thesis objectives and research questions *5*
- 1.4 Readers guide *5*

2 The carbon cycle on global andregional scales ***7***
- Abstract *8*
- 2.1 Introduction *9*
- 2.2 Overview of the carbon cycle *9*
- 2.3 The terrestrial C cycle *13*
- 2.4 Summary *30*

3 Modeling the terrestrial C cycle ***33***
- Abstract *34*
- 3.1 Introduction *35*
- 3.2 Review of terrestrial C-cycle models *36*
- 3.3 Scales and scaling in terrestrial C-cycle modeling *52*
- 3.4 The IMAGE-2 terrestrial C-cycle model *59*
- 3.5 Summary *79*

4 Modeling the global and regional consequences of ecosystem response to climate change through assessment of uncertainties ***81***
- Abstract *82*
- 4.1 Introduction *83*
- 4.2 Methodology *84*
- 4.3 Results *92*
- 4.4 Discussion *101*
- 4.5 Conclusions *104*

5 The importance of three centuries of climate and land-use change for the global and regional terrestrial carbon cycle ***107***
- Abstract *108*
- 5.1 Introduction *109*
- 5.2 Methodology *111*
- 5.3 Model set-up and experimental design *115*
- 5.4 Results & discussion *116*
- 5.5 Conclusion *127*

6 The terrestrial C cycle and its role in the climate-change policy ***129***
Abstract *130*
6.1 Introduction *131*

Section A:

6.2 Why is the C sink issue so controversial? Open questions, remaining issues and definitions *133*
6.3 Quantification of C sinks and biomass use *133*
6.4 Economic aspects *144*
6.5 Sinks and biomass energy as part of joint implementation (JI) and the clean development mechanism (CDM) *148*
6.6 Policy relevance and views of parties *149*
6.7 Discussion and conclusions on sink issue in general *151*

Section B:

6.8 Methodology *153*
6.9 Results *164*
6.10 Discussion *170*
6.11 Conclusions *175*

7 Conclusions ***177***
7.1. Introduction *179*
7.2. Research questions *179*
7.3. Overall conclusions *185*

References ***187***
Papers in peer-reviewed journals & books ***211***
Summary ***213***
Samenvatting ***223***
Acknowledgments ***233***
Curriculum Vitae ***237***

Chapter 1
Introduction

1. Introduction

1.1 Setting the scene

The earth's climate is changing (Klein Tank, 2004; Schär & Jendritzky, 2004; Trenberth & Jones, 2007) with even more changes are projected for the coming centuries (Meehl & Stocker, 2007). Up to the year 2100, for example global temperature may rise by 1.8 to 4.0 °C in comparison to the 1980-2000 average (best estimate, likely range 1.1–6.4 °C) and more frequent and intense extreme weather events may occur. The ongoing climate change has caused considerable impacts on nature, human health, and society. These impacts are projected to become more pronounced in the coming decades and centuries (e.g. EEA, 2004; Schellnhuber *et al.*, 2006; Fischlin *et al.*, 2007). Note that not all current and projected effects of climate change are adverse. The agricultural sector in some parts of Europe, for example, may benefit from a (limited) temperature rise.

In order to limit future climate change and its impacts, it is important to understand the causes of climate change. Gradually, we have come to realize that although the observed climatic changes are to some extent the result of natural causes (e.g. volcanoes and sun activity), most are very likely attributable to the increased concentrations of greenhouse gases (GHG) in the atmosphere (Hegerl *et al.*, 2007). The concentration of the most important greenhouse gas, carbon dioxide (CO_2) has increased from about 190-280 ppm in pre-industrial times up to about 380 ppm today (Denman *et al.*, 2007). The increase comes primarily from fossil fuel burning for energy generation, industrial processes such as cement production, and land-use changes such as deforestation.

Substantial reductions in GHG emissions are needed if the impacts of climate change are to be kept within manageable levels. At the global level, the challenge of mitigating climate change is being addressed by the United Nations Framework Convention on Climate Change (UNFCCC), aiming '*to stabilize atmospheric greenhouse gas concentrations at a level that would prevent dangerous anthropogenic interference with the climate system*' (UNFCCC, 1993). As a first step towards this ultimate objective, the Kyoto Protocol – which entered into force on 16 February 2005 – sets binding emission targets for the period, 2008-2012, for those industrialized/developed countries that have ratified it.

To determine the required long-term emission reductions, a thorough understanding of the global C cycle is needed. The C cycle consists of three major interacting compartments: the atmosphere, the oceans, and the terrestrial biosphere. The biosphere includes the part of terrestrial earth within which life occurs and in which biotic processes in turn alter or transform (http://en.wikipedia.org/wiki/Biosphere). Understanding the three compartments and their interactions is relevant because, for example, the terrestrial biosphere and the ocean sequester at the moment about 55% of the emitted CO_2 and thus slow down the atmospheric CO_2 increase. However, the future sequestration is uncertain, since the terrestrial biosphere, in particular, (i) consists of many processes that respond easily to environmental changes, and (ii) contains a considerable amount of carbon with a large turnover. A general decrease of the sequestration would imply more stringent emission reduction measures to achieve the stabilization of GHG concentrations in the atmosphere.

The terrestrial biosphere affects the C cycle in the following ways:

- through the substantial contribution of land-use changes to the atmospheric CO_2 increase (Houghton, 2003);
- through the sequestering of carbon by the remaining natural biosphere, which slows down the increase in atmospheric CO_2 concentration. This uptake is sensitive to environmental conditions and thus will change in the future;
- through the acceptance in the policy arena of the protection and establishment of forests as mitigation measure, recognizing that the terrestrial biosphere is important for climate change response, also in the short term (Watson *et al.*, 2000).

1.2 The problem statement

The terrestrial C cycle consists of many physical, chemical, and biological processes that operate on different temporal (e.g. hours to decades), spatial (e.g. stands, landscapes to biomes) and organizational (e.g. leaf, individuals, communities) scales. These processes are characterized by numerous interactions and respond quickly to changes in climate, hydrological aspects, and land use (Sabine *et al.*, 2004; chapter 2). The complex structure and dynamics in time and space lead to considerable uncertainty in projecting the future behavior of the terrestrial C cycle (Denman *et al.*, 2007).

Developing a more robust understanding of the role of processes involved in the terrestrial C cycle and their interactions poses a major challenge for improving the projections. In this thesis I adopt simulation models as an approach to deal with this challenge, i.e. to achieve more insights in the importance of different processes for the global C cycle. Simulation models have proven to be powerful tools to analyze the consequences for the C cycle of different assumptions, various parameter settings and scenarios. Furthermore, simulation models can help in exchanging information across different scales. The terrestrial C-cycle model of IMAGE 2 (Integrated Model for Assessing the Global Environment) forms the backbone of this thesis. IMAGE 2 is an integrated approach that includes both socio-economic (i.e. land and energy use) and natural (biogeographical and biogeochemical processes) dimensions with their interactions and feedbacks. Changes in land-use comprehensively include deforestation for cropland and pasture expansion, timber harvesting and reforestation. The model will be described in detail and applied to the past three centuries, and to various scenarios up to 2100. Furthermore, it will be used in assessing uncertainties of relevant processes. The position of the IMAGE-2 C-cycle model will also be discussed in a broader context by comparing the model's results with observed trends, and comparing the model's algorithm and results with other C-cycle models. These models range from highly aggregated and simple, to complex and process-based. Data demand and computing requirements increase exponentially with the complexity of these models. This will affect the balance between scientific rigor (i.e. the necessity for a high level of detail and, consequently, a limited number of scenario analyses if time and resources are limited) and applicability in a policy context (i.e. necessity for simplification of process simulations to analyze numerous baseline and policy scenarios).

1.3 Thesis objectives and research questions

The main objective of this thesis is *to assess the response of the terrestrial biosphere to changing environmental conditions and land use, and the consequences for the global and regional C cycle.*

To achieve this objective the following five research questions will be addressed in this thesis:

1. What are the main processes that determine the role of the terrestrial biosphere in the C cycle on global and regional scales?
2. What are the consequences of past and future changes in climate and land use on the regional and global terrestrial C cycle?
3. What are the key uncertainties in determining the response of the terrestrial C cycle to climate and land-use change?
4. What is the potential role of the terrestrial biosphere in stabilizing the CO_2 concentration in the atmosphere?
5. What is the applicability of intermediate-complexity, highly parameterized models in simulating the past, current, and future C cycle, especially in the context of climate-change policy development?

1.4 Readers guide

Chapter 2 presents the results of a comprehensive literature review of the general C cycle. This chapter provides the context for the role and behavior of the terrestrial C cycle. Further, it forms the theoretical background of this thesis, addressing particularly the first research question.

Modeling the terrestrial C cycle is described in *Chapter 3*. The chapter first summarizes different approaches to modeling the terrestrial C cycle, including the enumeration of all relevant processes and scales. Secondly, the terrestrial C-cycle model of IMAGE 2 is described in detail, including its latest parameterization. The arguments for selecting specific algorithms are positioned in the broader context of models and scales. Chapter 3 addresses mainly research questions 1 and 5.

Chapter 4 presents consequences of uncertainties in the ecosystem response to both land-use change and climate change for the global and regional C cycle. As such, the chapter addresses research questions 2 and 3. The uncertainties are related to the inclusion or exclusion of particular processes (e.g. including/excluding migration as an adaptive response by ecosystems to climate change), to different parameter settings (e.g. related to CO_2 fertilization and soil respiration), and the implications of different assumptions on land use and land cover. Various model experiments were set up to assess these uncertainties.

New estimates of the global and regional land use and natural C fluxes for the past three centuries are presented in *chapter 5*. This chapter addresses the question related to the main sources of the historical build-up of atmospheric CO_2 and the main sinks. This is especially relevant for research question 2.

Chapter 6 focuses on the quantification of one of the aforementioned three roles of the terrestrial biosphere in the global C cycle, i.e. the potential to mitigate the build-up of atmospheric CO_2 by establishing C plantations and managing existing C pools differently. These land-use activities constitute a major issue in international climate change policy development. As such the chapter addresses research question 4. The chapter consists of two sections:

- In section 1 issues are discussed in general terms that are related to the potential of different land-use options, as well as the economic and political implications, all in a policy context.
- In section 2 a new methodology is presented that quantifies the possible role of C plantations in mitigating the build-up of CO_2 in the atmosphere, and estimates of different sequestration potentials up to 2100 are presented.

The *chapters 3* to *6* include a comparison of IMAGE-2 results with observations and outcomes of other models, which addresses research question 5.

Chapter 7 presents the main conclusions, drawn from answering the research questions.

Chapter 2

The carbon cycle on global and regional scales

Abstract

This chapter introduces different elements and dynamics of the global and regional C cycle. A good understanding of different elements and processes is relevant for understanding the past, current, and possible future changes in climate. The current atmospheric CO_2 concentration (i.e. 380 ppm), for example, is about 100 ppm higher than in pre-industrial times. This increase is mainly the result of anthropogenic activities – primarily the burning of fossil fuels, industrial processes, and land-use changes. Nevertheless, the increase is less than could be expected on the basis of anthropogenic emissions. This is because oceans and the terrestrial biosphere have increased their net uptake and absorbed about 55% of the emissions.

Therefore, the terrestrial biosphere is of key importance for the C cycle. But what are the main processes for the inter-annual, annual, decadal, and century variation of the biosphere? Various natural (i.e. biochemical responses to environmental change like CO_2 and N fertilization, and climate) and human-induced (e.g. recent changes in management, ageing of forests after being planted early 20th century, and historical changes in land use) triggers have contributed considerably to the CO_2 changes in the atmosphere (1 – 2.2 Pg C yr^{-1} over past decades).

The understanding of the global C cycle has significantly improved in recent decades due to laboratory and field experiments, satellite observations, and modeling exercises. Still the uncertainty about the role of the biosphere is considerable. Some of these uncertainties are presented in this chapter. Despite the uncertainties, a robust finding among many simulation models is a projected stabilization of the terrestrial (as well as the ocean) sink over coming decades, followed by a decline. This would imply additional reduction efforts of the fossil fuel emissions required to achieve a stabilization of the atmospheric CO_2 concentration.

2 The carbon cycle on global and regional scales

2.1 Introduction

Anthropogenic activities – primarily the burning of fossil fuels, industrial processes and land-use changes – have led to emissions of various greenhouse gases (GHG) and have altered the global carbon (C) cycle (Denman *et al.*, 2007). The concentration of carbon dioxide (CO_2) – the most important GHG – has increased from 280 ppm in pre-industrial times up to about 380 ppm today. To understand and project future changes in the global C cycle, it is necessary to understand its underlying elements and processes. The C cycle consists of three main compartments: the atmosphere, the oceans, and the biosphere. The biosphere is that part of the terrestrial earth within which life occurs, and in which biotic processes in turn alter or transform (http://en.wikipedia.org/wiki/Biosphere). Each compartment consists of different C pools and exchanges C at different rates. The balance of the C cycle varies in time and space; this includes its dependency on environmental conditions and human activities.

The objective of this chapter is to summarize the current knowledge of the C cycle, including the pools, fluxes, and relevant processes. Although this thesis focuses on the terrestrial C cycle, all compartments are included in this chapter because of the strong interaction between them. For example, only about 45% of the historical anthropogenic CO_2 emissions remain in the atmosphere. The rest is removed by the ocean and terrestrial biosphere. The first section of this chapter describes the processes that determine the different C pools and the fluxes between them. In the subsequent section the role of the terrestrial biosphere in the C cycle will be evaluated in more detail. I provide ranges of C pools and rates of relevant processes, and show the geographical and temporal variation. Finally, certain terrestrial ecosystems will be described in the last section in more detail to accommodate their role in the global C cycle.

2.2 Overview of the carbon cycle

2.2.1 Introduction

Carbon (C) flows between the atmosphere, the oceans, and the terrestrial biosphere (consisting of a vegetation and soil carbon pool). The three compartments all consist of pools that store and exchange C at different rates and quantities, and with different lifetimes (Figure 2-1, Table 2-1). The largest amount of C by far (about 38,000 Pg C, Gruber *et al.*, 2004; CDIAC, 2006) is stored in the middle and deep ocean (Figure 2-1). This C is, however, relatively inert and, as such, less relevant for the C cycle in coming decades (Bolin *et al.*, 2000; Gruber *et al.*, 2004). Smaller but still considerably large pools are found in the terrestrial biosphere (2100–3000 Pg C), the surface layer of the oceans (600 Pg C) and the atmosphere (700–800 Pg C) (Grace, 2004; Denman *et al.*, 2007). The turnover rates of these compartments are high. The

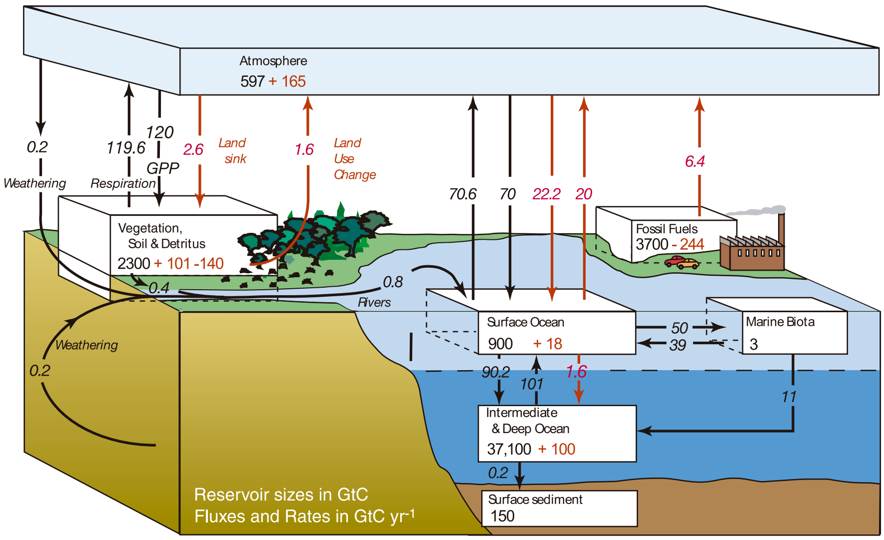


Figure 2-1 **Pools (in Pg C) and annual fluxes (in Pg C yr^{-1}) within the global C cycle. Fluxes are representative for the 1990s (Source: Denman *et al.*, 2007 based on Sabine *et al.*, 2004).**

ocean and terrestrial biosphere, for example, sequester annually about 92 and 61 Pg C, respectively, and emit almost a similar amount due to respiration (Figure 2-1). The high turnover rates give the surface layer of the ocean and the terrestrial biosphere a determining role in the C cycle at time scales ranging from months/seasons to centuries. The seasonal variation in the atmospheric CO_2 concentration, for example, is mainly the result of short-term behavior of the biosphere.

The anthropogenic C emissions are relatively small compared to the ocean and biosphere fluxes. They are, however, most relevant for the C cycle because they lead to a perturbation of a system that has been in a relatively steady state for decades, centuries, and even millennia (see next section). Over the last three centuries, the anthropogenic emissions due to fossil fuel burning and land-use changes have been about 300 Pg C (Marland & Boden, 2000) and 140–160 Pg C, (Houghton, 2003), respectively, implying emissions at a rate of about 1 Pg C.yr^{-1} and 0.5 Pg C yr^{-1}, respectively. High anthropogenic emissions have been measured since the 1980s (Table 2-1). The annual fossil fuel and land-use C emissions for the

Table 2-1 **Global CO_2 budget (in Pg C yr^{-1}) for different moments in time (note that positive numbers represent fluxes towards the atmosphere)**

	1980s	1990s	2000–2005
Atmospheric increase	3.3±0.1	3.2±0.1	4.1±0.1
Fossil fuel emissions	5.4±0.3	6.4±0.4	7.2±0.3
Ocean–atmosphere flux	-1.8±0.8	-2.2±0.8	-2.2±0.5
Land–atmosphere flux (section 2.3.4)	-0.3±0.9	-1.0±0.6	-0.9±0.6

Source: Denman *et al.*, 2007 based on Houghton, 2003; Sabine *et al.*, 2004).

period 1980–1989, for example, were estimated at 5.4 Pg yr^{1} and 1.3 – 2.0 Pg yr^{1}, respectively (Houghton, 2003). The measured CO_2 increase in the atmosphere was about 3.3 Pg C.yr^{1} during that period (Denman *et al.*, 2007), which is about 45% of the total anthropogenic emissions. The oceans and terrestrial biosphere responded by increasing their uptake and storing the remainder (Sabine *et al.*, 2004).

As such, the terrestrial biosphere represents currently a carbon sink. The size of this sink has, however, been under scientific debate. Houghton (2003) presented relatively high sink fluxes for the 1980s and 1990s (Table 2-1), whereas DeFries *et al.* (2002), Achard *et al.* (2002) came with lower estimates, mainly due to considerably lower deforestation rates (section 2.3.4 and chapter 5 of this thesis). Denman *et al.* (2007) recently estimated the net terrestrial sink at about 1 Pg C yr^{1} over the last 15 years on the basis of these earlier studies. The relatively low terrestrial estimate implies a more balanced contribution of the different sinks in the global C cycle.

2.2.2 The atmosphere

The atmosphere is a mixture of gases, mainly nitrogen (78% of dry atmosphere) and oxygen (21%). Among the remaining gases are various so-called greenhouse gases (GHG). GHGs have the ability to intercept and re-emit infra-red radiation that is emitted from the earth's surface. Despite their minute concentration, GHGs are crucial for the climate on earth. Without them the global average temperature would be about 32^{o}C lower than it is now (i.e. -18 ^{o}C instead of the current +14^{o}C global mean temperature average), too cold to support contemporary life and especially the modern human society. One of the most important GHGs is carbon dioxide (CO_2).

Historically, the atmospheric CO_2 concentration has shown considerable fluctuations (Figure 2-2). Over the last 400,000 years, for example, the concentration varied between 190 ppm (=parts per million) during the ice ages and 280 ppm during warm periods (Siegenthaler *et al.*, 2005). Prior to the industrial period (i.e. before 1750), the CO_2 concentration fluctuated between 260 and 280 ppm (Monnin *et al.*, 2004). With respect to the inter-annual or decadal scale, the atmospheric CO_2 concentration varies mainly due to fluctuations in biospheric uptake (Grace, 2004; Denman *et al.*, 2007). An important trigger of these fluctuations is the presence or absence of an El Niño event[1]. Such events are, in general, marked by decreased terrestrial C uptakes (partly compensated by increased oceanic C uptake) and thus high CO_2 growth rates in the atmosphere Denman *et al.*, 2007). Note that the annual fluctuation too is mainly caused by biospheric behavior. The concentration is high in the winter months for the Northern Hemisphere, because temperature limits the uptake rates of the biosphere. In contrast, high uptake rates in the summer lead to a drop in the atmospheric CO_2 concentration.

---

[1] El Niño is caused by the rise in sea-surface temperatures in the equatorial Pacific Ocean, which influences atmospheric circulation and, consequently, rainfall and temperature patterns in specific areas around the world. It occurs every 4 to 12 years (http://www.weathersa.co.za/References/elnino.jsp).

The atmospheric CO_2 concentration has increased considerably since the beginning of the industrial era (Monnin *et al.*). At present the atmosphere currently stores 2500–2900 Pg CO_2 (or 700–800 Pg C), equivalent to a concentration of about 380 ppm. This concentration level exceeds the highest concentration in the last 400,000 years (i.e. 280 ppm) by about 100 ppm (Sabine *et al.*, 2004). As a result of this increase in CO_2 and other GHGs, the climate on earth is changing (Hegerl *et al.*, 2007). The global temperature, for example, has increased 0.8±0.2 °C, compared to pre-industrial time periods (Trenberth & Jones, 2007). The observed temperature increase is unusual in terms of both magnitude and rate of temperature change. Likewise, more frequent and more severe heat waves, storms and floods have been observed (Klein Tank, 2004; Schär & Jendritzky, 2004; Trenberth & Jones, 2007).These climatic changes have their effect on the C cycle in the ocean and terrestrial biosphere.

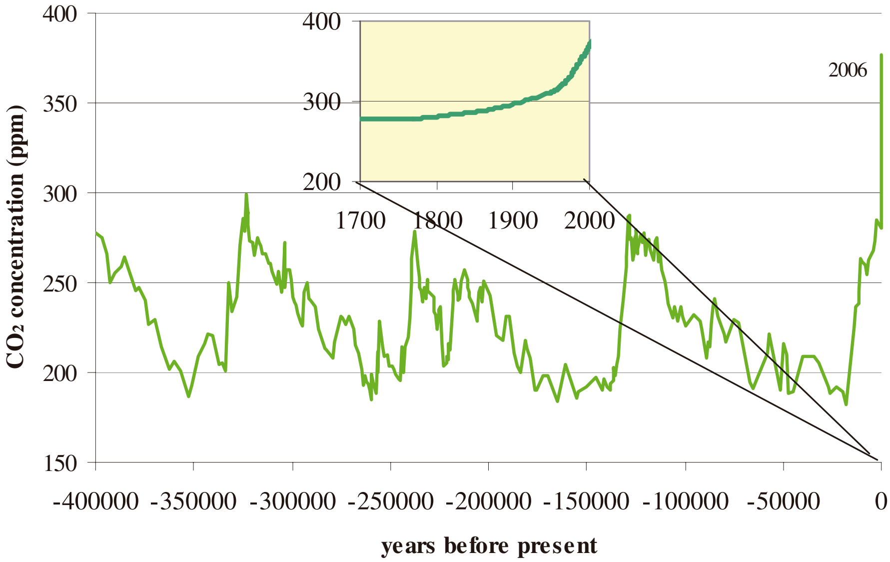


Figure 2-2 Reconstructed record of the atmospheric CO_2 concentration over the last 400,000 years (Source: Mann, 2002).

2.2.3 Oceans

Oceans store approximately 38,000 Pg C, about 50 times the amount stored in the atmosphere (Sabine *et al.*, 2004; Denman *et al.*, 2007). About 98% of this carbon is stored in the middle and deep ocean layers (Figure 2-1). The atmosphere exchanges CO_2 with the surface layer of the ocean. This layer stores about 900 Pg C, which is exchanged with the atmosphere on time scales of hundreds of years (Denman *et al.*, 2007). The net result of a two-way exchange between oceans and atmosphere is a current annual uptake of about 1.8–2.2 (average 2) Pg C yr^{1} (Denman *et al.*, 2007; Figure 2-1; Table 2-1). This uptake occurs especially at high latitudes (due to the cold temperature conditions), whereas oceans near the tropics release CO_2. The uptake flux is determined by various biological, physical, and chemical processes. Biological processes lead, for example, to CO_2 sequestration in the form of shells of calcium carbonate or as organic carbon consumed by zooplankton that sink as dead organisms.

The overall CO_2 sequestration rate of the oceans changes only slowly. Factors that determine the exchange are the seawater temperature (warming leads to emissions), nutrient supply (especially nitrogen and phosphorous), salinity, and alkalinity (Watson *et al.*, 2000; Denman *et al.*, 2007). The latter depends, in turn, on the atmospheric CO_2 concentration, leading to a decreasing uptake as the atmospheric CO_2 concentration increases.

Furthermore, C is stored in the ocean as a result of a C flow from the land via rivers and to some extent also groundwater. This flux consists of a natural (about 0.8 Pg C yr^{1}) and anthropogenic (0.1 Pg C yr^{1}) component. About half of this flux is re-emitted back to the atmosphere close to the land. The remaining (mainly inorganic) C enters the long-term oceanic C cycle.

The future uptake of CO_2 in the oceans is projected to decrease due to various physical, chemical, and biological factors (Sarmiento *et al.*, 1998; Denman *et al.*, 2007). The chemical uptake capacity of the ocean surface layers decreases under increasing temperature and atmospheric CO_2 levels, since CO_2 becomes less soluble in warmer water. The decrease may be counterbalanced by an increased biological uptake. Marine organisms (e.g. phytoplankton) increase their CO_2 uptake in a warmer climate because of increased activity, whereas increasing precipitation reduces the uptake capacity. Note that the future biological uptake is uncertain. It depends heavily on total nutrient composition (e.g. nitrogen to phosphorous ratio) and the most limiting nutrient (Watson *et al.*, 2000b). In regions where the marine productivity is limited by deep ocean nutrients, the biological uptake could decrease because climate change increases the ocean stratification (Sarmiento *et al.*, 1998). In other regions, the biological activity can increase due to increased nutrient (e.g. iron) availability caused by anthropogenic input (Watson *et al.*, 2000b).

2.3 The terrestrial C cycle

The terrestrial biosphere plays an important role in the global and regional C cycle, and thus the global climate system. This occurs through biophysical interactions and biogeochemical exchanges with the atmosphere. These processes either slow down the increase in atmospheric CO_2 (so-called negative feedbacks) or accelerate it (i.e. positive feedbacks). With respect to the biophysical interactions, the terrestrial biosphere largely determines the amount of energy received from the sun that is returned to the atmosphere (Denman *et al.*, 2007). Through evapotranspiration from plants and soils, for example, water is evaporated at the cost of energy (i.e. latent heat), which consequently can not be used to warm up the atmosphere (i.e. sensible heat). With reference to its biogeochemical role, the terrestrial biosphere stores large amounts of carbon in its compartments (Figure 2-1). Here, different processes are described that determine the C dynamics within the biosphere and exchange rates with the atmosphere.

2.3.1 Terrestrial carbon processes

The CO_2 uptake and release of the terrestrial biosphere is determined by a number of processes that are sensitive to climate, atmospheric CO_2, moisture availability, and land use. Within the terrestrial biosphere, plants take up CO_2 by diffusion through the stomata of leaves (globally about 270 Pg C yr^{-1}, Ciais, 1997 #4188}). More than 50% of this CO_2 diffuses back to the atmosphere without becoming part of biogeochemical processes within plants. A basic biogeochemical process within plants is photosynthesis, where CO_2 is converted under the influence of “active radiation” (400–700 nm wave length) into carbohydrates that serve as raw material for further processes. The amount of C that is fixed through photosynthesis is called *gross primary production* (GPP). The amount that is really taken up by plants, allocated to and incorporated in new plant tissues is defined as *Net Primary Production* (NPP) (Figure 2-3; Table 2-2). As such NPP includes all increments in the biomass of leaves, stems, branches, roots, and reproductive organs. NPP has been measured in many ecosystem types across the world (see also next section). The remaining part of the C is lost by *autotrophic plant respiration*. Most of the C fixed through NPP also returns back to the atmosphere through *heterotrophic soil respiration* (Rh), and *disturbances*. The former process is the decomposition of soil organic matter by bacteria and fungi, which consume most of the organic material that enters the soil through dying plant material. Several soil C pools can be distinguished with different C contents, chemical composition, and different bacteria and fungi composition. As result they have often different decomposition rates. The difference between NPP and Rh is called *Net Ecosystem Productivity* (NEP) or *Net Ecosystem exchange* (NEE). It represents the amount of carbon that is annually stored in the terrestrial biosphere.

When also accounting for C losses due to fires, land-use change, harvest, and erosion, the total C flux is called *Net Biome Productivity* (NBP). NBP is what the atmosphere “sees” as the net terrestrial uptake over long periods (i.e. periods of decades to centuries). NBP is zero in an ecosystem that is in a steady state, since C losses balance NPP. But NBP has been positive for many decades, although fluctuating a lot (Houghton, 2003; Grace, 2004; Van Minnen *et al.*, 2008). Thus terrestrial ecosystems currently represent a net C sink. This sink is likely caused by a combination of an increased length in growing season, especially in high latitudes (Churkina *et al.*, 2005), changes in forest management, ageing of forests after being planted in the early 20th century (Neilson, 1993; Kaipainen *et al.*, 2004; Phat *et al.*, 2004), and CO_2 and N fertilization (Schlesinger & Lichter, 2001; Nemani *et al.*, 2003; Novak *et al.*, 2004, Milne & van Oijen, 2005). Various models project NBP (and NEP) to possibly decrease during this century. They may even turn the terrestrial biosphere into a C source (see also next section). The terrestrial C sink also varies depending on the year, which is one of the main reasons for the year-to-year variation in atmospheric CO_2 concentration (Denman *et al.*, 2007). The inter-annual variation of the sink is triggered particularly by the aforementioned El Niño. El Niño events are typically characterized by decreased NPP rates. These lower rates are caused by high temperatures with less precipitation –also resulting in more droughts and more frequent fires – in some parts of the world like the productive regions of the Amazonian forest. In other regions, El Niño events lead to more cloudiness and more intense precipitation in southeastern Asia, resulting in decreased NPP rates (Prentice *et al.*, 2001).

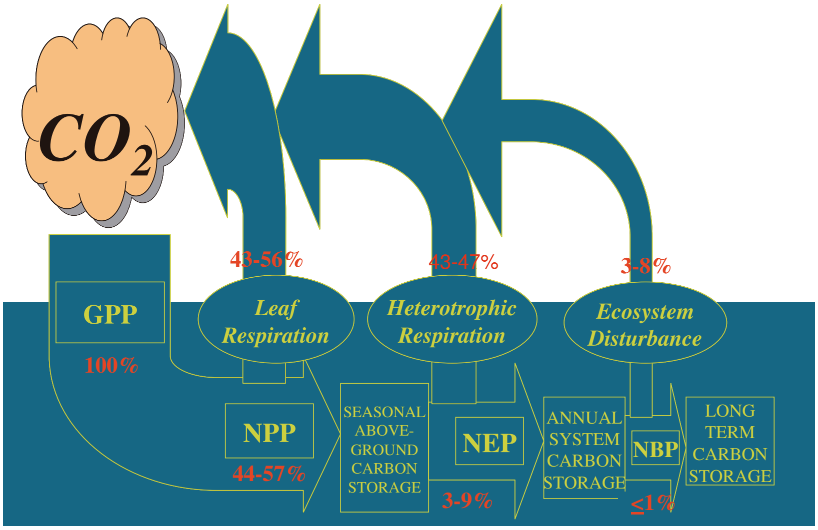


Figure 2-3 Terrestrial biosphere processes and related average CO_2 fluxes (based on Steffen *et al.*, 1998).

Water is a fundamental prerequisite for all ecosystem processes that determine the terrestrial C cycle. Plants take up water through roots and lose it through transpiration from the leaves. The amount of water available to plants for maintaining the water balance depends on the precipitation in an area, soil characteristics, and runoff from and to other areas. The precipitation available for plant growth depends on the amount of water reaching the rooted soil layer. In many ecosystems (especially forests) precipitation is lost through *interception* in the canopy. The interception, in turn, depends on the type of precipitation (i.e. rain, snow, dew), ecosystem characteristics (e.g. canopy density, leaf type, age, etc.), and weather variables (i.e. rainfall intensity, wind, solar radiation, humidity, temperature). In total, interception can account for up to 35% of the annual precipitation (Waring &

Schlesinger). Furthermore, the water available for plants depends on the *infiltration* rate into the soil versus the amount of surface runoff, the *evaporation* from the soil, the rise of water from the subsoil, and *uptake* characteristics of the plant (e.g. root density).

The *maximum (or potential) transpiration* of plants is determined by the concentration gradient of water vapor between the leaves and the surface atmosphere. The water vapor gradient, in turn, can be derived from the temperature in the air and leaves, and the relative humidity. The maximum transpiration is reduced under circumstances that affect the stomatal opening of leaves. Examples of such circumstances are less solar radiation (e.g. during the night), changing CO_2 levels in the atmosphere and a reduced soil water availability. Land cover determines the *actual transpiration* due to different land-cover characteristics (Nosetto *et al.*, 2005). The most relevant characteristics are the surface roughness and the total leaf area.

2.3.2 Carbon pools and fluxes within the terrestrial biosphere

Global pools and fluxes

Globally, the terrestrial biosphere stores about 2100 – 3000 Pg C, divided into 466 – 660 Pg C in the vegetation and 1460 – 2300 Pg C in soils (Table 2-4). The total terrestrial C storage is about three times the amount in the atmosphere and the surface layer of the ocean (Sabine *et al.*, 2004; Denman *et al.*, 2007). The range is caused, for example, by differences in definitions (e.g. some soil compartments), the total area included and various uncertainties (especially related to the soil carbon budget, which is difficult to measure).

Global annual terrestrial GPP is estimated at 120 Pg C yr^1 (Denman *et al.*, 2007). On the annual base, global NPP estimates for the recent decades range between 53 – 68 Pg C yr^1 (Table 2-2). The estimates are based on integration of field measurements (e.g. WBGU, 1998), remote sensing, atmospheric measurements (e.g. Potter *et al.*, 2004) and modeling the historical C cycle (e.g. chapter 5). The range is due to uncertainties in land cover and land use (Houghton, 2003; Lambin *et al.*, 2003), and in the response of the terrestrial biosphere to environmental changes like climate, $CO_{2,}$ and N fertilization. NPP fluxes vary with the study, especially for tropical regions (Berthelot *et al.*, 2005; see next section). Furthermore, the range is caused by the different measurement methods and the different time periods of the studies. Regarding the time period, Potter *et al.* (1999) and Nemani *et al.*(2003) showed that the global NPP increased about 6% over the last decades.

The global NEP flux over the last decades is estimated at between 3 and 10 Pg C yr^1 (Watson *et al.*, 2000; Cox, 2001; Cramer *et al.*, 2001; Prentice *et al.*, 2001; Grace, 2004; Schaphoff *et al.*, 2006). Note that there is a wide range of uncertainty, especially in soil processes (Grace, 2004), and a considerable inter-annual variability (Valentini *et al.*, 2000). Furthermore, the low end of the range often represents model results that implicitly include some effects of disturbances.

Table 2-2 Overview of different global NPP estimates, areas and densities

Source	NPP (Pg C yr $^{-1}$)	Area (Gha)	Area-based NPP (Mg C ha^{-1}yr^{1})
Lieth (1975)	61.0		
Atjay *et al.* (1979)	59.9	14.9	4.0
Goudriaan & Ketner (1984)	61.9	12.1	5.1
Olson *et al.* (1985)	60.2	15.1	4.0
Box (1988)	67.8	14.9	4.5
Seino & Uchijima (1992)	61.2	14.9	4.1
Polglase & Wang (1992)	59.8	12.2	4.9
Friedlingstein *et al.* (1994)	53.5	15.1	3.5
WBGU (1998)	61	14.9	4.1
Potter *et al.*	57.9		
Nemani *et al.* (2003)	54.5		
Grace (2004)	62.6	14.9	4.2
Sabine *et al.* (2004)	57.5	17.5	3.2

Looking at the possible future, we see that various models have projected an increasing NEP flux up to the middle of this century, followed by a stabilization (Cramer *et al.*, 2001;Scholes & Noble, 2001), a decline (Lucht *et al.*, 2006; Schaphoff *et al.*, 2006) or even a shift towards a C source (Cox *et al.*, 2004). The decrease (and shifts towards a C source) is due to increasing soil respiration and decreasing NPP fluxes in different parts of the world. These projections are also surrounded with substantial uncertainty due to uncertainties in future regional climate (Schaphoff *et al.*, 2006) and the response of the biosphere to future climate and atmospheric CO_2 (Cramer *et al.*, 2001; Friedlingstein *et al.*, 2006).

When CO_2 emissions due to land-use changes are excluded, the global residual terrestrial C sink is estimated to be in the range of 0.9 – 2.4 (average 1.7) Pg C.yr^{1} over the 1980s and 2 –3 (average 2.6) Pg C.yr^{1} in the 1990s (Table 2-3). Recent observations indicate that the global sink is still increasing, possibly up to 2.9 Pg C.yr^{1} (Körner, 2003; Grace, 2004). The location of the current residual sink is under discussion (see next section).

Similar to the NEP flux, many models project that also the residual sink can peak in the mid 21st century, followed by a decrease (Hoch *et al.*, 2003; Friedlingstein *et al.*, 2006; Lucht *et al.*, 2006). Evaluating the different processes shows that the C uptake may saturate at 3.7 – 8.6 Pg C yr^{1} if only changes in atmospheric CO_2 are considered. If the changes in climate are also taken into account, the residual sink is projected to diminish by the end of this century (Lucht *et al.*, 2006). The terrestrial biosphere might even turn into a C source (Scholes & Noble, 2001; Hoch *et al.*, 2003; Friedlingstein *et al.*, 2006).

Table 2-3 Residual terrestrial sink estimates (excluding land-use change emission)

Source	Area	1980s ($Pg\ C\ yr^{1}$)	1990s ($Pg\ C\ yr^{1}$)
McGuire *et al.* (2001)	Global	0.9 ± 0.6	
Prentice *et al.* (2001)	Global	1.9 ± 1.6	
Watson *et al.* (2000)	Global		2.3 ± 1.3
Grace, 2004	Global		2.85
Houghton, 2003	Global	2.4 ± 1.1	2.9 ± 1.1
DeFries *et al.*, 2002	Global	0.9	2.1 ± 1.2
Scholes & Noble, 2001	Global		2 – 3
Achard *et al.*, 2002	Global		2.2 ± 1.0
Denman *et al.*, 2007	Global	1.7 ± 1.7	2.6 ± 1.5
Van Minnen *et al.*, 2007	Global	1.8	2.1
Cramer *et al.* (2004)	Tropics		0.64 ± 0.21
Janssens *et al.*, 2003	Europe		0.11
Mollicone *et al.*, 2003	Europe		
Liski *et al.*, 2003	Boreal & temperate forests	0.88	0.71–1.1
Fang *et al.*, 1998	China	0.02	

The NBP – the net atmosphere-to-land flux including changes in land use – is estimated to be about 0.3 ±0.9 Pg $C.yr^{1}$ during the 1980s and 1.0 ±0.6 Pg C yr^{1} during the 1990s (Achard *et al.*, 2002; DeFries *et al.*, 2002; Houghton, 2003; Denman *et al.*, 2007). The NBP fluxes are comparable across these studies, despite the underlying components that differ (i.e. land-use emissions and residual sink). These processes counterbalance each other. High values for land-use emissions (e.g. Houghton, 2003) are accompanied by high residual uptake rates, whereas low deforestation emissions (e.g. (Achard *et al.*, 2002) are associated with low residual sinks.

C pools and fluxes across ecosystems and regions

The C pools and fluxes are not homogenously distributed across the world, but differ geographically, seasonally and between ecosystem types (Table 2-4). Ecosystem types that store large quantities of C are forests, grasslands, and wetlands. Considering their relevance for the C cycle, these ecosystems will be described in more detail.

Globally, forests cover more than 4 billion hectares ($=40 \times 10^{12}\ m^2$) or about 28% of the terrestrial biosphere (FAO, 2001; Grace, 2004). About half the forest area is located in developed countries (mostly temperate and boreal types of forests) and half in developing (mostly tropical) countries.

Table 2-4 Global C pools and NPP fluxes differentiated over ecosystems

Ecosystem	Area (10^9 ha)	Total C pool (Pg C)	NPP (Pg C yr $^{-1}$)
Forests Tropical Temperate Boreal	4.2 (28%) 1.9 1.0 1.3	1146 – 1640 (46–59%) 428 – 1032 159 – 401 207 – 559	25 – 33 (41–52%) 15.2 – 21.9 5.5 – 8.1 2.4 – 4.2
Grasslands & savannas	3.5 (24%)	508 – 634 (21–25%)	14 – 20.5 (23–33%)
Agriculture	1.6 (11%)	131 – 169 (5 – 8%)	4 (7%)
Arctic tundra	1 (7%)	117 – 146 (5%)	0.5
Wetlands	0.4 (3%)	230 – 450 (8–13%)	0.2
Others (e.g. deserts)	4.2 (27%)	200 – 359 (8–12%)	4.9 (7%)
TOTAL	15	2137 – 2996	55 – 63

Source Silver, 1998 ;WBGU, 1998; Gitay *et al.*, 2001; Nemani *et al.*, 2003; Grace, 2004; Sabine *et al.*, 2004; Fischlin *et al.*, 2007.

Forest ecosystems are important for the global C cycle, firstly, because they store nearly half the terrestrial C (Table 2-4). If considering only the vegetation C pools, forests even store 80–90% of the carbon (WBGU, 1998; Körner, 2003a). The largest fraction of this pool (i.e. about 60%) is stored in tropical forests (Sabine *et al.*, 2004). Note that the C pools and fluxes vary even considerably between tropical forest types, depending on the type of forest and degree of disturbance. The living biomass of tropical rain forests, for example, ranges between 160–190 t C ha^{-1} compared to dry forests with only 30–60 t C ha^{-1}. Boreal forests also contain a considerable amount of carbon in the soil (i.e. 200–500 Pg C, WBGU, 1998; Sabine *et al.*, 2004).

Secondly, forest ecosystems are important for the global C cycle because of the considerable C exchange between forests and the atmosphere. Nearly all the forests around the world currently sequester C. The observed NPP of tropical forests, for example, is up to 10 Mg C ha^{-1}.yr^{1}, while the average natural C sink is 0.5 – 1 Mg C ha^{-1} yr^{1}, with maximum values of about 3 Mg C ha^{-1}.yr^{1} (Baker *et al.* , 2004; Grace, 2004). Including the C losses due to deforestation (see next section too), tropical forests still represent either a small C sink (Hougton, 2002; Cramer *et al.*, 2004; Grace, 2004) or are carbon neutral (e.g. (McGuire *et al.*, 2001), 2001; Gurney *et al.*, 2002; Rayner *et al.*, 2005). Thus, the remaining natural tropical forests must be substantial C sinks considering the substantial land-use fluxes.

The main terrestrial C sink is allocated to temperate and boreal forests, sequestering 0.7 – 1.1 Pg C yr^{1} over the recent decades. This range is based on field studies (e.g. Fan *et al.*, 1998; Hougton, 2002; Janssens *et al.*, 2003) as well as modeling exercises (Gurney *et al.*, 2002; Wofsy, 2001). The main reasons for this C sink in temperate and boreal forests are recent changes in forest management, the development of these forests (compared to their life expectancy), and environmental changes like climate, CO_2 and N deposition (Valentini *et al.*, 2000; Gurney *et al.*, 2002; Körner, 2003b; Grace, 2004). Note that the C sink in especially boreal forests fluctuates, due, for example, to its high sensitivity to (a variable) climate. These forests are, for example, often a C source in warm or dry years (Valentini *et al.*, 2000). Regarding the longitudinal partitioning of the northern residual sink, it is most likely to be equally distributed over the forests in northern America, Europe and northern Asia (Gurney *et al.*; 2002; Rayner *et al.*, 2005; Denman *et al.*, 2007). The NEP of temperate mature forests in the USA, for example, is between 2.1 – 2.7 Mg $C.ha^{-1}.yr^{1}$ (Birdsey *et al.*, 2006), whereas similar forests in Europe sequester 1.9 Mg $C.ha^{-1}.yr^{1}$ (Janssens *et al.*, 2003).

Natural grasslands are also widely spread across the world. The total grassland area is about 3.5 billion hectares, of which 65% is located in warm and tropical regions (WBGU, 1998; Sabine *et al.*, 2004; Table 2-4). Much grassland around the world has been converted into agricultural land over the past decades, resulting in a declining amount (Meyer & Turner, 1998). Natural grasslands are important for the global C cycle because of the large extent and the considerable carbon storage, on the one hand, and their sensitivity to climate change and direct human influence on the other (Parton *et al.*, 1994). Regarding the former, the global C storage in the living biomass of natural grasslands is 33 – 85 Pg C, while the total C pool in grassland soils is in the range of 279 and 559 Pg C (WBGU, 1998; Sabine *et al.*, 2004). Large differences are found across the world for grasslands too. The C storage in the living biomass of tropical grasslands is generally higher than in grasslands in temperate regions, whereas the soil C pools are comparable in both parts of the world (Sabine *et al.*, 2004). Global NPP estimates of grasslands vary between 8.6 and 15 Pg C yr^{1} (compared to 3–6 Mg C ha^{-1} yr^{1}). The productivity decreases due to human influences, causing a reduced C storage and soil erosion (Burke *et al.*, 1991; Ojima *et al.*, 1993). The observed NPP range is, in particular, determined by the seasonal distribution of precipitation (Ojima *et al.*, 1993). This is because many natural grasslands in the world are water limited (Meyer & Turner, 1998). Because of the dependency on water, climate change (especially seasonality and precipitation) may have a considerable effect on the total C balance of grasslands.

Wetlands also store large amounts of carbon, mainly in soils (240 – 455 Pg C, Gorham, 1991;WBGU, 1998, Sabine *et al.*, 2004). The majority of the wetlands and C storage can be found in boreal and arctic regions. Tropical wetlands are less relevant (total C storage about 70 Pg C; Diemont, 1994), although the largest C densities have been observed here (up to 5 Mg C $.ha^{-1}$). Furthermore, wetlands are important for the C cycle because of the risk of a significant loss of their soil C pool under climate change. The optimum annual average temperature for C sequestration of most wetlands is between 4 and 10°C. This can be currently observed in much of the southern-boreal and northern-temperate zones. With projected temperature increases, conditions are likely to exceed the optimum range. Numerous arctic wetlands may even disappear entirely under temperate increases in the range of 2–3 °C (Hitz & Smith, 2004). Likewise, changes in precipitation affect the species composition of wetlands and, as such, the functioning (Keddy, 2000). All these changes can result in a change in wetlands from a C sink into a C source.

2.3.3 Environmental conditions influencing the terrestrial C cycle

In the previous section basic biogeochemical processes were described that determine the C cycle within the terrestrial biosphere (i.e. GPP, NPP, soil respiration, natural disturbances). It also has been shown that the terrestrial biosphere is currently a C sink. To understand this sink better and to project possible future changes, it is critical to understand the dependency of the processes on environmental conditions such as climate, atmospheric conditions, nutrient supply, and water availability. Changes in these conditions will either increase the C uptake in the biosphere (and lower the CO_2 concentration, negative feedback) or decrease it (positive feedback). The net result of all the effects collectively depends on the combination and intensity of the individual environmental conditions.

Relevant environmental conditions that will be described in more detail in this section are (i) atmospheric CO_2 concentration; (ii) temperature; (iii) precipitation and soil moisture availability; (iv) nutrient availability and (v) land cover or ecosystem composition. Note that, although various effects have been quantified experimentally, it is often difficult to quantify the outcome for the entire C cycle. For example, many of these conditions interact, implying that the effect of a single condition depends on other conditions (Waring & Schlesinger, 1985).

Atmospheric CO_2 concentration

Many studies have shown that increasing atmospheric CO_2 levels enhance plant growth (see reviews by Bazzaz, 1990; Hougton, 2002; Woodward & Lomas, 2004). In general, two mechanisms can be distinguished on how increased CO_2 levels affect plant growth (Figure 2-4). Firstly, increasing CO_2 levels enhance the CO_2 diffusion rate between the atmosphere and the plant stomata and increase photosynthesis. This is the *CO_2 fertilization effect*. This growth enhancement due to elevated CO_2 has been shown by many field, laboratory, and modeling studies (Körner & Diemer, 1987; Mooney *et al.*, 1991; Bazzaz & Fajer, 1992; Larcher, 2003). Secondly, while CO_2 diffuses into the leaves of plants through stomata, water is lost (i.e. transpiration). Under increased CO_2 levels in the atmosphere, stomata can be partly closed. As a result, a plant can keep CO_2 uptake constant, while reducing its transpiration rates. This enables plant growth under more water-limited conditions, thus providing a broader distribution. This effect is called *water-use efficiency (WUE)*, where WUE is defined as the biomass production per unit water “consumed” by the plants (Mooney *et al.,* 1991; Mooney & Koch, 1994).

The *CO_2 fertilization effect* depends on numerous plant properties. The photosynthesis of so-called C3 plant species[2] (e.g. grass species in temperate regions and tree species) is, for example, more responsive to elevated CO_2 than that of C4 plant species[2] (e.g.

---

[2] C_3 and C_4 are two different photosynthetic pathways, each with a specific response to increasing atmospheric CO_2 levels.

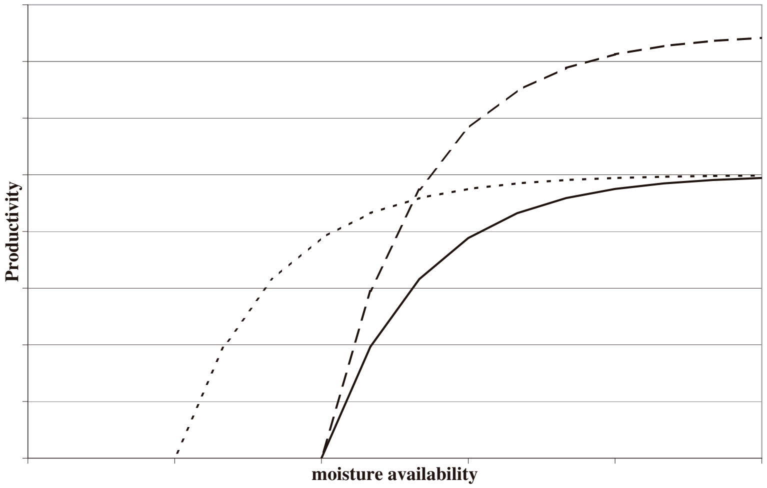


Figure 2-4 **Illustrative plant response to increased atmospheric CO_2 levels. Solid line: current productivity; dashed line: increased productivity due to CO_2 fertilization and dotted line: changes in distribution due to WUE (Van Minnen *et al.*, 1995).**

grass species in tropical regions) (Bazzaz, 1990; Bowes, 1993). Likewise, herbaceous plants benefit more from high CO_2 levels than woody plants (Körner, 2003). Other plant properties that influence the sensitivity of plant species to CO_2 changes are the presence of special storage organs or fruits, leaf position, leaf width, and the age and the physiological stage of a plant. Seedlings, for example, are more responsive to higher CO_2 levels than mature plants because of higher activity levels (Davis & Zabinski, 1992; Körner *et al.*, 2005).

The extent of the CO_2 fertilization effect also depends on environmental and local conditions, e.g. altitude, temperature and moisture, and nutrient availability. Plants growing at high altitudes are more responsive than low-latitude plants since the CO_2 pressure decreases with increasing altitude. Körner & Diemer (1987) found that plants growing at 2600 m show twice as large a photosynthetic response to doubled CO_2 compared with plants growing at 600 m. Likewise, limited NPP increases have been found under nutrient-limited circumstances (Goudriaan & De Ruiter, 1983; Bazzaz & Fajer, 1992), although the nutrient efficiency ratio of plants can theoretically increase at enhanced CO_2 levels (for example, due to a improved nutrient use in enzyme processes; Bowes, 1993).

Note that the strength of the CO_2 fertilization effect is still controversial, especially in natural vegetation and over continental scales (Heath *et al.*, 2005, Denman *et al.*, 2007; Fischlin *et al.*, 2007). Despite the consistency among experiments (e.g. Larcher, 2003;Körner, 2003) and model projections (Leemans *et al.*, 2002; Friedlingstein *et al.*, 2003; Schaphoff *et al.*, 2006), the feasibility of the large increase in terrestrial C uptake due to increasing CO_2 levels (in some regions of the world a doubling or even tripling of the current-day growth,Van Minnen *et al.*, 2006) can be questioned. Growth and, with this, the CO_2 fertilization effect may be limited due to other environmental constraints – especially nutrient and water availability (Alexandrov *et al.*, 2003; Körner *et al.*, 2005) and ozone (Sitch *et al.*, 2007). Furthermore, the permanency of CO_2 fertilization is uncertain. Some recent studies suggest that the CO_2 fertilization effect could saturate and that the growth stimulus diminishes after a number of years due to increasing respiration rates (e.g. Cramer *et al.*, 2001; Körner *et al.*, 2005). In view of these considerations, Novak *et al.* (2004) and Norby *et al.* (2005) concluded that an additional C uptake of plants due to increasing atmospheric CO_2 levels is also likely to be on a large scale (up to 25%), but that this stimulus is less than expected from physiological principles.

Temperature

Temperature is a determining factor of many physiological processes within the biosphere that affect the C cycle. Temperature affects plant growth through its effect on the length of the growing season and the development phases within it, photosynthesis, transpiration, and autotrophic plant respiration (Alexandrov *et al.*, 2003). Furthermore, temperature also affects soil decomposition and is a critical determinant of ecosystem distribution,

The *development* of plants can only be achieved if sufficient energy is available. The growing season starts if a certain temperature is exceeded. Above this minimum temperature, processes like leaf expansion start. The growing season ends if temperatures drop below these "thresholds" (Larcher, 2003). The different development stages within a growing season are also related to certain temperatures. After passing a minimum threshold temperature, for example, germination of spores and seeds increase exponentially with temperature. Likewise, the flower formation of many plant species is induced at certain temperature thresholds. Certain woody plants like Norway spruce (Picea abies), for example, require a period of low temperature (so-called chilling requirement) to flower normally in the successive year (Waring & Schlesinger, 1985; Larcher, 2003). If the chilling period is too short, the trees will not flower and cones will not develop.

The effect of temperature on *photosynthesis* can be characterized by an optimum curve (Larcher, 2003). It starts at a certain temperature and increases until a maximum photosynthetic rate is reached. Beyond this optimal temperature the photosynthetic rate declines rapidly due to decreased efficiency of various physiological processes. Plant *respiration* starts at low rates and increases exponentially with increasing temperatures. At high temperatures heat damage occurs causing respiration to cease. The consequence of the different response of photosynthesis and respiration is that NPP increases up to a maximum value (at T_{opt}). At higher temperatures NPP drops down to zero at T_{max} where photosynthesis equals plant respiration. Minimum, optimum, and maximum temperature ranges are plant-species specific (Woodward *et al.*, 1995; Waring & Running, 1998; Larcher, 2003). The optimum temperature of temperate species, for example, is commonly in the range of 15 – 25°C, whereas it varies for tropical species between 30 – 35°C.

Temperature indirectly affects plant growth through its effect on the *hydrological cycle* and thus water availability. Firstly, temperature changes affect cloud formation and thus the precipitation pattern in certain regions (Denman *et al.*, 2007). Secondly, temperature changes result in changed water uptake of plants. Low temperatures inhibit root growth and reduce the uptake capacity of plants. The sensitivity varies considerably among plant species (Waring & Schlesinger, 1985). Northern and alpine tree species (e.g. Scots pine, Pinus sylvestrus), for example demonstrate a larger uptake under cold conditions than more temperate species (e.g. Douglas fir, Pseudotsuga menziesii). Thirdly, temperature affects the water storage and transport within plants, and the transpiration rate. With respect to the transpiration rate, increasing temperatures result in larger vapor pressure deficits between leafs and atmosphere. This leads either to increased transpiration or decreased CO_2 uptake (due to stomata closure).

Soil decomposition depends on temperature because microbial activity potentially increases exponentially with increasing temperature (Knorr *et al.*, 2005; Aerts, 2006; Shaver *et al.*, 2006). Note that this relationship does not necessarily imply that the regional decomposition increases continuously under global warming (Melillo *et al.*, 2002). Increasing temperatures will, for example, only lead to increased decomposition rates under sufficient moisture availability (Angert *et al.*, 2005; Aerts, 2006). Furthermore, initially increased decomposition rates might return to pre-warming rates within a limited number of years (Giardina & Ryan, 2000). This acclimation is, however, still under discussion (see review by Knorr *et al.*, 2005; Davidson & Janssens, 2006).

Temperature also affects the C cycle through its effect on the geographical distribution of species in multiple ways. First, as mentioned above, temperature is one of the determinants of photosynthesis. Because the photosynthetic response to temperature changes is species specific, (a change in) temperature affects the competitive abilities of a species against others. Secondly, temperature is also relevant for species distribution in terms of low temperatures. Plant species have different tolerances against low temperatures. Most woody species in the (sub)tropics, for example, will not survive (long) periods with freezing temperatures (Woodward, 1987), whereas various other plant species require a chilling period for germination and thus for the presence in an area.

Precipitation and moisture availability

Water is a fundamental prerequisite for plant growth. Low water availability results in a decreased photosynthesis caused by stomata closure, and thus reduced CO_2 uptake, and various physiological perturbations. Furthermore, a reduced transpiration flux results in a biophysical feedback on the climate system because the sensible heat flux increases at the cost of latent heat. This, in turn, results in a regional temperature increase, indirectly affecting the C cycle (Denman *et al.*, 2007). Two critical points can be distinguished with respect to the precipitation effect on plant growth: the threshold between full and reduced photosynthetic capacity, and the zero point for CO_2 uptake (Larcher, 2003). The position of both points determines the susceptibility of a species to water shortage. Many tree species, for example, are very sensitive to water deficiencies whereas most herbaceous crop plants are more tolerant. Broadleaved tree species will compensate for dry conditions by earlier leaf abscission, and as such reduce the growing period. The consequences of dry conditions could be large for the terrestrial C cycle. Cox *et al.*, 2004, for example, used a climate model that projects severe reductions in precipitation and thus moisture deficits in tropical regions. As a result, tropical forests were languishing by about 2050, turning the entire terrestrial biosphere from being a C sink into a C source.

Precipitation also determines the soil-water content. This, in turn, influences the decomposition process (Waring & Schlesinger, 1985). Under very wet conditions (i.e. when soils are saturated), soil decomposition is limited due to the lack of oxygen. Such anaerobic conditions diminish (but not completely stop) the microbial activity. Under dry conditions the microbial activity also appears to be reduced (Waring & Running, 1998).

Changes in precipitation (through its effect on moisture availability) affect the geographical distribution of plant species, land-cover characteristics and as such the terrestrial C cycle. The main reason is that plant species have different moisture requirements and different tolerances to survive a period with insufficient moisture. So-called CAM species (e.g. pineapple), for example, are able to withstand dry conditions because of stomata closure during the day (thus minimizing transpiration) and C uptake during the night (Larcher, 2003). Furthermore, changing precipitation patterns affect the frequency and extent of disturbances (Apps, 2003; Lynch *et al.*, 2004). The occurrence of such disturbances is a prerequisite for the occurrence of various plant species, whereas other species are negatively affected by more disturbances.

Nutrient availability

Nitrogen (in different forms), phosphate, and cations (mainly K^+, Ca^{2+}, Mg,$^{2+}$, and Cl^-) are essential nutrients for various ecosystem processes. These nutrients become available through atmospheric deposition, inflow through surface runoff and biogeochemical soil processes. They are lost through water outflow (leaching and surface runoff), and other biogeochemical soil processes. Note that the net availability for a plant is not linear with the sum of the aforementioned sources; this is because the availability also depends on the uptake potential of plants. This, in turn, depends on root characteristics and the dominant mycorrhiza association[3]

---

[3] Mycorrhiza are symbiotic fungi in the soil that help plants in the uptake of nutrients.

(Woodward & Kelly, 1997). Since soil decomposition is a critical source of nutrients for plants, increasing decomposition rates (e.g. due to increasing temperature) may lead to increased nutrient (mainly nitrogen) availability for plants. As a consequence, plant growth might become stimulated if one of the nutrients has been the limiting factor.

The terrestrial C cycle is affected by nutrient availability through the effects on plant growth and soil processes. With respect to the former, nutrient availability affects photosynthesis directly (i.e. part of the photosynthetic processes) and indirectly (i.e. by affecting size and structure of leaves and roots and the course of plant development). In general, a nutrient shortage reduces the photosynthetic capacity. A shortage of magnesium, for example, can lead to a drop in the photosynthesis to less than one-third (Larcher, 2003). In the end, the development of the plants becomes abnormal. The growth stimulus under increased CO_2 levels might even become blocked due to nutrient shortage (Schlesinger, 2000; Hungate *et al.*, 2003). One remaining uncertain issue is the effect of nutrient shortage on the large-scale C cycle. Whereas small-scale (leaf to plants) responses have been shown (where photosynthetic capacity rises with increasing nitrogen availability in a linear proportion until other factors evoke saturation, Waring & Schlesinger, 1985), entire ecosystems may already become adjusted to a low nutrient availability and remain photosynthesis at a constant level by reducing the nutrient content in their compartments (Larcher, 2003). This is the so-called nutrient-use efficiency (Linder, 1987). Note that an excessive availability of nutrients can result, firstly, in a stabilizing photosynthesis, followed by a depressed rate. The latter is caused by the harmful or even toxic effect of various compounds (Larcher, 2003).

Soil decomposition is affected by the nutrient status as much as by climatic variables (Berg & Tamm, 1994). Differences in nutrient status is one of the main causes of the spatial variation in soil decomposition rates (Polglase & Wang, 1992). Furthermore, it causes considerable changes in decomposition rates over time, varying from very fast for fresh litter to slow rates for more humus types of soil organic matter. In general, microbial activity increases (and as such decomposition rates) with the availability of nutrients. The C/N ratio is often a good predictor of the decomposition rate (Mosier, 1998). Compounds like lignin with a high C/N ratio are relatively resistant and can be decomposed only by certain fungi in the soil (Melillo, 1985). The decomposition of the overall soil organic matter decreases with increasing content of these compounds.

Ecosystem distribution

The terrestrial C cycle is also affected by changes in climate through the effect on ecosystem distribution and species composition (Woodward, 1987). The other way around, changes in land-cover distribution affect climate (and thus indirectly the C cycle) because of ecosystem-specific C dynamics (i.e. different C storage in the various pools), and biogeofysical feedbacks. Considering the latter, ecosystems have different albedos and surface roughness, affecting the radiation balance, water balance, and heat fluxes (Bonan, 2001; Schaeffer *et al.*, 2006).

A critical question in evaluating the effect of climate change on ecosystem distribution is whether ecosystems are able to adapt to rapid changes in climatic and atmospheric conditions (Cramer *et al.*, 1999; Jump & Penuelas, 2005). An adaptation possibility to survive these changes is the migration towards more appropriate sites. Migration of plant species consists of three successive stages: (i) dispersion of seeds and/or propagules into new regions; (ii) colonization and establishment at new sites and (iii) growth, maturation, and reproduction on these sites (Huntley & Webb, 1989; Neilson, 1993). These migration stages are described in detail in Van Minnen *et al.* (2000).

Climatic conditions are relevant for all stages. They determine, for example, the year-to-year variability of the seed production and dispersal. Likewise, climate is an important determinant of the frequency and extent of disturbances, which are needed for the colonization of various plant species (Sykes & Prentice, 1996). Based on these migration stages, plant species can be grouped into three classes, characterized by their life strategy (Van Minnen *et al.*, 2000).

The first class consists of species with a large seed production, a large dispersal range, a primary establishment strategy, and a fast growth potential (e.g. herbs, shrubs, and tree species like *Betula spp.*). The species “invest” mainly in energy in rapidly entering new suitable sites. They show, however, a low acclimation potential to climate change. The net migration rate is mainly defined by the dispersion properties. The net vulnerability of these species to climate change therefore depends on the rate of change, i.e. whether there is sufficient time to migrate towards new locations (Grime, 1993).

The second class consists of “competitive” species or so-called “*ecological generalists”*. Although species in this class (like Quercus spp.) are slow growers, they are widely distributed because of high competitive abilities and extremely long life cycles. As such, they are able to endure relatively many environmental changes within a location. Their survival is only threatened when the environmental conditions deteriorate rapidly and become unsuitable (e.g. flooding, extreme colds).Under such conditions the distribution of ecological generalists becomes threatened because of limited capabilities to migrate (due to short dispersal distance, and slow growing capacity).

The third major life strategy consists of so-called *environmental specialists*. Species within this class are stress-tolerant, and often grow under severe environmental conditions where other species cannot survive. They are, however, also characterized by low competitive abilities and a small investment of energy in dispersal capabilities. Environmental specialists have therefore low migration rates and are easily out-competed by other species if these are capable of existing in that particular area.

Consequently, environmental specialists are most vulnerable to environmental changes.

A problem in evaluating the effect of vast climatic changes on species distribution is the uncertainty in possible migration rates. Although large-scale vegetation shifts in response to climate change have occurred historically (e.g. Davis & Sugita, 1997; Araujo *et al.*, 2004), the response needed to cope with anticipated climate change is likely to be a magnitude greater than shifts that have occurred historically. If these migration rates, derived from vegetation shifts during the Holocene, represent maximum rates, these will be inadequate in the near future (Araujo *et al.*, 2004). Climate change will then result in degraded ecosystems and likely in the disappearance of many species, as well as to large C emissions into the atmosphere (Solomon & Leemans, 1997). Several studies on isolated plant individuals and some introduced species, however, indicate that migration rates could be higher than those derived from historical records (Kullman, 1996; Pitelka, 1997). But even then, changes in ecosystem composition will occur since species respond differently to changing climatic conditions, having consequences for the terrestrial C cycle.

2.3.4 The role of human disturbances in the terrestrial C cycle

Humans disturb ecosystem functioning and C storage through land-use changes. These lead, for example, to deforestation or a rearranged composition of many ecosystems. Disturbances occur at any spatial and temporal scale (Apps, 2003). Whether a disturbance on one scale is relevant on other scales depends on the effect of the disturbance, and the resilience of the ecosystem. An ecosystem might respond to become temporarily out of equilibrium and return to the same steady state situation in time. Hence a disturbance has only little long-term effect. But disturbances may also have large effects on structural or functional processes within an ecosystem and bring it into a complete new balance with a new steady state. This will be observable on the large and longer scale (Meyer & Turner, 1998).

Deforestation has been responsible for almost 90% of the historical land-use related CO_2 emissions (WBGU, 1998). Table 2-5 depicts estimates of deforestation rates and the related C emissions over the past centuries. Estimations of the deforestation in the 20th century indicate a 15–20% clearance of all natural forests around the world (Waring & Running, 1998; Watson *et al.*, 2000). The associated CO_2 emissions for the 1850–2000 period have been estimated at 123–200 Pg C or 0.8–1.3 Pg C yr^{1} (Table 2-5, chapter 5), compared to the cumulative historical fossil fuel emissions of about 300 Pg C (Marland & Boden, 2000). Large-scale deforestation of tropical forests occurred during the past decades. Still earlier, forests were also cleared elsewhere, with the bulk in the temperate regions of Europe and eastern America in the early 20th century (Meyer & Turner, 1998; Klein Goldewijk *et al.*, 2007). Some of the deforested areas in North America and Europe have been reforested again in recent decades and are now (partly) responsible for the current sink in high latitudes.

Table 2-5 Deforestation rates (in Mha.yr^{-1}) and related C losses (in Pg C yr^{-1})

Source	Period	Region	Annual deforestation	C loss
Dixon *et al.*, 1994	1980s	Global	15.4	2.3
FAO	1990s	Global	16.1	
Houghton, 2003	1850–2000 1980s 1990s	Global		1.0 2.0 2.2
Levy *et al.*, 2004	1850–1989	Global		1.3
DeFries *et al.*, 2002	1980s 1990s	Tropical forests	8.1 8.0	0.7 1.0
Fearnside	1981–1990	Tropical forests		2.4
Houghton, 2003	1850–2000 1980s 1990s	Tropical forests	 15.4 15.8	0.7 1.9 2.2
McGuire *et al.*, 2001	1980s	Tropical forests		1.6
WRI, 1991	1970s & 1980s	Tropical forests	12	
Achard *et al.*, 2002	1990–1997	Humid tropical forests	5.8	0.6
FAO, 2001	1970s & 1980s	Humid tropical forests	6.4	
Lambin *et al.*, 2003	1990–1997	Humid tropical forests	5.8	
Nepstad *et al.*, 1999	1980–1990	Brazil	2	0.3
Fearnside	1988–1998	Brazil	1.6	0.4
Phat *et al.*, 2004	1990–2000	SE Asia	2.3	0.5

Note that the extent of the deforestation and related CO_2 emission still carry a large uncertainty in the global C budget (Foley & Ramankutty, 2004). For example, the land-use related emissions from tropical deforestation for the period 1980–1990 vary between 0.6 (DeFries *et al.*, 2002) and 2.4 Pg C yr^{1} (Fearnside, 2000). Main causes of this variation are the difficulty in measuring deforestation (even with recent remote sensing techniques), the application of different methods, different assumptions on the carbon densities of the removed forests, and the use of different definitions (Houghton, 2003; Cramer *et al.*, 2004). Referring to the latter, different definitions of forest and cropland have, for example, been used, and it is often unclear whether a cleared forest is left bare or undergoes re-growth. With regard to the different methods, satellite-based estimates (Achard *et al.*, 2002; DeFries *et al.*, 2002) point to much smaller emissions than the more statistics-based methods of, for example Houghton (2003). It is, however, too early to state that the latter type of estimates was overestimating the historical deforestation fluxes due to the other causes of uncertainty (see also chapter 5 of this thesis).

Not only forests became affected by humans, but so do many savanna and natural grassland areas in the world that have been converted, mainly for livestock grazing. Meyer & Turner (1998) indicated that about 16% of the grassland areas around the world have disappeared over the last decades, compared to early 20th century. These land-use changes had different effects on the amount of C stored in biomass and soil. In some cases, areas have been extensively cleared, resulting in large emissions. Activities in other areas like fire suppression and introduction of new tree and shrub species has led to increased carbon storage.

Besides the biogeochemical consequences (i.e. CO_2 emissions instead of biospheric C storage), deforestation also affects the C cycle indirectly through biogeophysical feedbacks, i.e. the effect on the radiation balance, the subsequent climate system and the biospheric response (Schaeffer *et al.*, 2006). The effect is, however, in either direction, depending on the type of vegetation that replaces the forest (Denman *et al.*, 2007). Replacement of forests with shorter vegetation, along with the normally assumed higher albedo may cool the surface. If, however, the new vegetation has less foliage or cannot access soil water as successfully, warming may occur. Furthermore, land-use changes also lead to more aerosols in the atmosphere and cloud formation, both also affecting the earth radiation balance (Hoffman *et al.*, 2002).

2.4 Summary

In this chapter different elements and dynamics of the global and regional C cycle have been introduced. A good understanding of different elements and processes is relevant for understanding the past, current, and possible future changes in climate. The current atmospheric CO_2 concentration (i.e. 380 ppm), for example, is about 100 ppm higher than in pre-industrial times. This increase is mainly the result of anthropogenic activities – primarily the burning of fossil fuels, industrial processes, and land-use changes. Nevertheless, the increase is less than could be expected on the basis of anthropogenic emissions. This is because oceans and the terrestrial biosphere have increased their net uptake and absorbed about 55% of the emissions.

Therefore, the terrestrial biosphere is of key importance for the C cycle. But what are the main processes for the inter-annual, annual, decadal, and century variation of the biosphere? Various possible natural (i.e. biochemical responses to environmental change like CO_2 and N fertilization, climate) and human-induced triggers (e.g. recent changes in management, ageing of forests after being planted in the early 20th century, and historical changes in land use) have contributed considerably to the CO_2 increase in the atmosphere.

The understanding of the global C cycle has significantly improved in recent decades due to laboratory and field experiments, satellite observations and modeling exercises. Still the uncertainty about the role of the biosphere is considerable. This uncertainty is, for example, caused by the uncertainty in how the large-scale CO_2 fertilization effect will develop during this century. Likewise, with respect to the soil response to climate change, many models assume an approximate doubling of the specific decomposition rate of various ecosystems for every 10°C warming. However, this is not yet confirmed by observations at the whole ecosystem level for decadal time scales in forests and grasslands. Despite these uncertainties, a robust finding among many simulation models is a projected stabilization of the terrestrial (as well as the ocean) sink over the coming decades, followed by a decline. This would imply additional reduction efforts of the fossil fuel emissions required to achieve a stabilization of the atmospheric CO_2 concentration.

One remaining challenge is to improve the integration of the different elements of the terrestrial biosphere. Many elements can not be considered in isolation because of interactions. A better integration may improve global and regional projections, and decrease the uncertainties further. This would allow a comparison of the consequences of different parameterizations of the C cycle with the consequences of land use and socio-economic development. A step in this direction will be attempted in the remaining chapters of this thesis, using the terrestrial C cycle model of the Integrated Model to Assess the Global Environment (IMAGE 2). In these chapters, the possibilities of simulating the terrestrial C cycle will be assessed, in general, with a focus on the IMAGE-2 C-cycle model, in particular. Furthermore, results will be presented of an analysis of the consequences of uncertainties in land use, climate change, and vegetation response for the global and regional C cycle. Finally, the importance of the different factors and processes in the global C cycle will be assessed on different geographical scales.

Chapter 3

Modeling the terrestrial C cycle[1]

---

[1] The description of the IMAGE-2 terrestrial C-cycle model is based on:

Van Minnen, J.G., B. Strengers, B. Eickhout & K. Klein Goldewijk (2006) Simulating carbon exchange between the terrestrial biopshere and atmosphere; in Bouwman, A. F., Kram, T., and Klein Goldewijk, K. (eds.), *Integrated modelling of global environmental change: An overview of IMAGE 2.4*, Netherlands Environmental Assessment Agency, (MNP), Bilthoven, pp. 113-130

Van Minnen, J.G., R. Leemans & F. Ihle (2000) Defining the importance of including transient ecosystem responses to simulate C-cycle dynamics in a global change model. *Global Change Biology* **6**: 595-611

Van Minnen, J.G., K. Klein Goldewijk & R. Leemans (1995) The importance of feedback processes and vegetation transition in the terrestrial carbon cycle. *Global Ecology and Biogeography Letters* **22**: 805-814

Klein Goldewijk, K., J.G. Van Minnen, E. Kreileman, M. Vloedbeld & R. Leemans (1994) Simulation the Carbon Flux between the Terrestrial Environment and the Atmosphere. *Water, Air and Soil Pollution* **76**: 199-230

Abstract

The main objective of this chapter is to describe the terrestrial C-cycle model of IMAGE 2. I motivate its structure and algorithms by entering the model into the broader discussion on terrestrial C-cycle models and scales.

Terrestrial C-cycle models differ with respect to objectives and scales. These models have also become more complex and comprehensive, changes that in general have led to a more accurate understanding of the terrestrial C cycle and more robust projections. Nevertheless, many terrestrial C-cycle models include some crude assumptions (for example, on ecosystem management and land use). Furthermore, we should consider if the increasing detail –including a higher data demand and increasing computational expanses – is needed in the context of the model objectives?

Subsequently, I introduce the issue of scales and scaling in terrestrial C-cycle modeling. Given the pervasive influence of scales on any conclusions reached, it is essential that assessments be explicit when referring to the geographic and temporal extent for which a study is valid.

In the last section I describe in detail the IMAGE-2 terrestrial C-cycle model. This model includes components that have been derived from various other C-cycle model types such as gap, terrestrial ecosystem, and biogeographical models. Compared to more simple, early terrestrial C-cycle models, IMAGE 2 is implemented on a geographical grid, and includes physiological and biogeographical processes. Compared to more complex models, various generalized processes and statistical relationships have been implemented in IMAGE 2 with respect to processes and scales. These simplifications have consequences for the applicability of the IMAGE-2 C-cycle model. The strength of the model lies in the long-term perspective and integration of various biogeochemical, biogeographical, and socio-economic dimensions. Furthermore, IMAGE 2 has the advantage of estimating policy-relevant indicators and is able to run large numbers of simulations and scenarios.

3. Modeling the terrestrial C cycle

3.1 Introduction

Simulation models use *mathematical expressions* to describe the behavior of a system in an abstract manner (Bratley *et al.*, 1987). The mathematical expressions are based on scientific theories and assumptions. Compared to the real world, the structure and processes are simplified in any simulation model. Simulation models have diverse purposes: predictions/projections (i.e. assessing responses to changing driving forces), performance, training, education, and an improved understanding/discovery of relationships between the elements of a system (Goudriaan *et al.*, 1999). Furthermore, a general purpose of any model is to enable its users to draw conclusions about the real system by studying and analyzing the model.

Because of the increasing complexity and scales (in time and space) involved, developing ecological-oriented simulation models has become a scientific challenge and a political need. The models should improve the scientific understanding of the major dynamics of ecosystems on different scales. They should, for example, provide information on how ecological information (e.g. ecosystem structure) derived on local scales can be used on regional or global scales. In addition, ecological-oriented simulation models should allow for (policy-related) projections in order to assess the long-term (e.g. towards the end of this century) responses of ecosystems to environmental and anthropogenic changes (Cramer & Field, 1999). Ecological-oriented models have, for example, been developed to assess the consequences of air pollution, land-use change and changes in atmospheric CO_2 and climate.

The main objective of this chapter is to present the terrestrial C-cycle model of IMAGE 2, and to motivate its structure and algorithms. Before presenting the details of this model, I want to position it first in a broader context by providing an overview of different types of simulation models that simulate the regional and global terrestrial C cycle. I call all these model types “terrestrial C-cycle models”, although they differ in scale, objective, level of comprehensiveness, and applicability (Table 3-1). The comparison, for example, is used to discuss the processes included in the IMAGE-2 terrestrial C-cycle model and its parameter settings. Subsequently, I will introduce the issue of scales and scaling in terrestrial C-cycle modeling, since the role of the terrestrial biosphere[2] in the global C cycle includes many processes that operate over a range of temporal, spatial, and organizational scales. I will then provide details of the IMAGE-2 terrestrial C-cycle model and end with a short synthesis in which I position this model in the broader context of models and scales.

---

[2] Defined as that part of the terrestrial earth within which life occurs, and in which biotic processes in turn alter or transform (http://en.wikipedia.org/wiki/Biosphere)

3.2 Review of terrestrial C-cycle models

Understanding the complexity of the terrestrial C dynamics in relation to anthropogenic activities and environmental changes – including future trends and assessment of possible policies – can be achieved through modeling. Various types of terrestrial C-cycle models have been developed, ranging from highly aggregated and simple, to complex process-based. Note that data demand and computing requirements generally increase with the complexity of models.

In this section I will categorize different types of terrestrial C-cycle models. Such models have been reviewed and classified in many ways over the past decades. Authors have often focused on particular types of terrestrial C-cycle models (e.g. empirical versus process-based, Venevsky, 1994; equilibrium versus dynamic models, Klein Goldewijk & Leemans, 1995), scales (local versus regional and global, Mohren *et al.*, 1994) and processes. Goudriaan *et al.* (1999) have provided one of the few reviews that assess the entire spectrum of models. After adopting and extending this classification, I ended up with six main categories of terrestrial C-cycle models, each of them having a number of model subcategories (Table 3-1). The six main categories are: (i) models for managed terrestrial ecosystems such as agriculture and forests, (ii) community dynamics models, (iii) biogeographical models, (iv) biogeochemical models, (v) biogeophysical models, and (vi) combined modeling approaches (Table 3-1). The categories differ with respect to the focus (i.e. ecosystem structure and composition versus ecosystem functioning) and scales. With regard to scales, models have often been developed for a particular temporal and spatial scales (Figure 3-1), although information on different scales is often included (Walther *et al.*, 2002). With regard to the focus of C-cycle models, the categories (i), (iv) and (v) include models that simulate ecosystem functioning from a patch-up to a global scale, but generally ignore/simplify changes in ecosystem structure and composition. Models that deal with these issues (but, in turn, ignore/simplify general ecosystem functioning) belong either to category (ii), which includes ecosystem structure from stand-up to regional scale, or (iii) ecosystem composition on regional up to global scale. These two categories also differ with respect to the driving forces (Table 3-1). Category (vi) consists of models types that combine different principles. The IMAGE-2 model – as an example of such a combined model – uses concepts of gap models in its ecosystem re-growth module, along with basics of biogeochemical models to simulate the C dynamics and biogeographical models for ecosystem distribution (Table 3-1, see also section 3.4).

For each of the categories I describe the main objectives, the scales involved, the level of comprehensiveness, and useful references (Table 3-1). The "level of comprehensiveness" is based on the current state of the model types. Biogeochemical models, for example, have developed from regression-based models in the 1970s (e.g. MIAMI model (Lieth, 1975), with their parameterized and globally aggregated processes in only a few ecosystems and no spatial explicitness), into models that

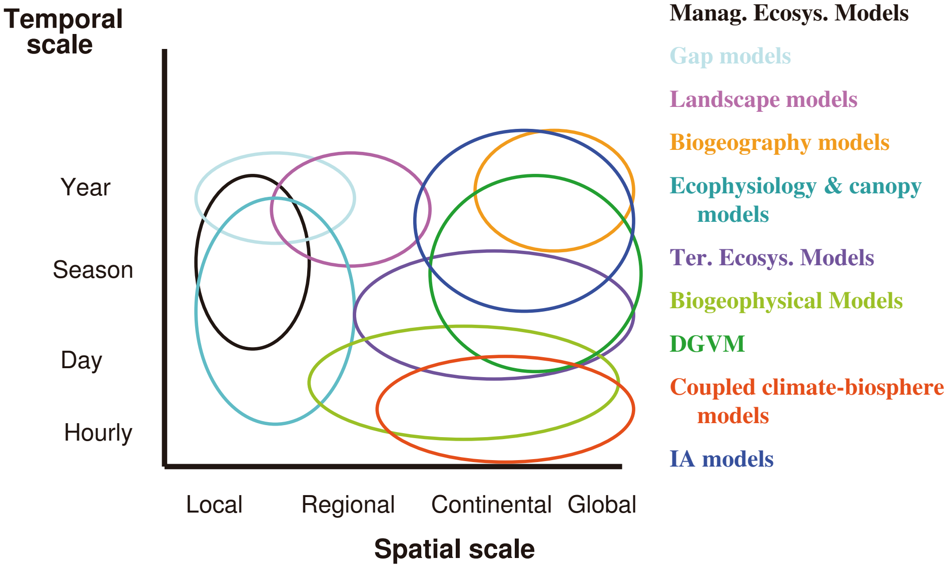


Figure 3-1 Temporal and spatial domain of different types of terrestrial C-cycle models.

contain detailed mechanistic relationships to assess the C, and nutrient and water fluxes (e.g. Bethy, Knorr & Heinmann, 2001 or Hybrid, Friend *et al.*, 1997). Principles of these more detailed biogeochemical models are often used in Dynamic Global Vegetation Models (DGVMs) to simulate the C dynamics (Table 3-1).Whereas Table 3-1 provides a general overview of the model types, Table 3-2 summarizes their current algorithm with respect to the terrestrial C cycle: how is ecosystem functioning or composition calculated, what are main drivers/input variables, and what is useful output?

3.2.1 Models for managed terrestrial ecosystems

Models for managed terrestrial ecosystems have been developed for agriculture crops, grassland ecosystems, and forests. All of them aim at simulating the development of certain plant categories as a function of weather/climate, and site conditions (e.g. expressed in water and nutrient availability). Whereas most crop and grassland models have been developed for mainly research purposes, forest yield models also serve as a source of information for forest managers.

Agricultural crop models have been developed to simulate the development of crop types through their growing season and productivity. Originally, these models simulated the productivity as a function of weather, and the availability of water and nutrients (Goudriaan *et al.*, 1999; Table 3-1). Because of climate change, crop models were extended with respect to the physiological processes included (e.g. growth became dependant on atmospheric CO_2 concentration) and the model applicability over multiple areas. The original objectives have been extended to include support of food security issues (e.g. Parry *et al.*, 2004; Tubiello *et al.*, 2007).

Grassland models have been developed to better understand the consequences of different management systems and environmental changes (e.g. climate change) on the grassland productivity. Some of the models have also been linked to economic models in order to evaluate the consequences of different economic and policy measures (e.g. tax). Note that some grassland models include links to the biogeochemical processes. I describe such models (e.g. the CENTURY model) under the biogeochemical models. Grassland models are, in general, essential to extending experimental results to coarser scales, and exploring the consequences of rare events and multiple management measures (e.g. nutrient amendments & changes in cutting frequency) (Goudriaan *et al.*, 1999).

Forest yield models have, in particular, been developed for forest management, although they are also used for research purposes (Mohren & Burkhart, 1994). Originally, these models describe, empirically, the development (i.e. height and thickness) of trees within a forest stand using the so-called site index. This is essentially a statistical relationship between tree growth (and related C storage), with specified stem density and certain environmental conditions on a location/site. The soil nutrient and water status is included in this site index. Based on the height and thickness, the models estimate the total wood volume in an area. Original forest yield models are less applicable for estimating forest growth under (fast) changing environmental conditions. Therefore these models have become more mechanistic so as to include a link to climate (e.g. Peng, 2000). Some other models (e.g. FORSOL, Van Minnen *et al.*, 1995) use allocation fractions and lifetimes in order to estimate the total C pools in trees and soil.

An advantage of the managed ecosystem models is their simplicity, but also accuracy (because of the link to long measurements series). Furthermore, they have been frequently used, especially to evaluate consequences of different management regimes, but are less applicable under rapidly changing environmental conditions (especially for forests). Furthermore, the models focus, in general, on biomass productivity, less on total C dynamics (although there are exceptions, such as the FORECAST model, Kimmins *et al.*, 1999).

3.2.2 Community dynamics models

Community dynamics models form the first category of models that focus on the simulation of ecosystem structure and composition rather than on ecosystem functioning. Two subtypes can be distinguished, i.e. *gap/patch* models and *landscape* models (Table 3-1).

There are many examples of gap/patch models used in the context of climate change (see reviews by Shugart & Smith, 1996, Bugmann *et al.*, 1996). These models share a common structure of modeling the establishment, growth, and mortality of individual plants over time on the scale of a patch. Interactions between plants are explicitly included by using light availability. The main objective does not focus on the individual plant level, but on simulating the structure of a patch and its composition (Table 3-1). Environmental constraints that are generally included in gap/patch models to reduce the potential growth are temperature (often represented by growing degree days in a growing season), soil moisture availability (expressed as a ratio of actual and potential evapotranspiration) and light. Some gap models also include nutrient availability as a constraint by using a linear function with availability (e.g. Post & Pastor, 1996). The relevance of these constraints differs among the ecosystem considered. Forest-oriented gap/patch models generally focus on light and temperature, whereas the most critical resources in models for scrublands and grasslands are most often below ground, i.e. water and nitrogen (Goudriaan *et al.*, 1999). The overall environmental constraint is, in general, implemented as a multiplier of the individual constraints. Gap/patch models differ largely in complexity, partly related to the scale of application (see section 3.3). Generic approaches have been introduced especially for the large-scale applications. Fulton (1993), Lischke *et al.* (1998) and Bugmann *et al.* (2000), for example, aggregated individual trees into "stochastic groups of individuals".

Landscape models simulate ecosystem dynamics on the landscape scale (Table 3-1). A landscape can be described in different ways (Goudriaan *et al.*, 1999):

(i) As non-interactive patches, where a landscape consists of multiple, non-interactive elements, making landscape configuration less relevant,
(ii) As spatially connected patches, where a landscape consists of patches that alter each others dynamics; here, interactions take place via the exchange of material (e.g. runoff water), or the propagation of disturbances like forest fires or land-use changes;
(iii) As spatially connected individual plants, especially relevant in inhomogeneous ecosystem types like savanna. In such cases it is relevant to take into account the spatial position of an individual plant/tree relative to its neighbors.

The aforementioned gap/patch models are applicable in the case of non-interactive patches. Markov chain models (e.g. Logofet & Lesnaya, 2000) and cellular automata (e.g. Wu *et al.*, 2003) are examples of modeling approaches that deal with spatially connected patches. Despite this differentiation, many landscape models simulate patch dynamics and ecosystem growth (including climate effects) with algorithms comparable to the patch/gap models, although often with a lower complexity or coarser resolution (Perry & Enright, 2006). The ForeL landscape model, for example, uses an algorithm based on the FORCLIM model to simulate patch dynamics and climate effects on tree establishment, growth, and mortality for different landscapes in the USA (Busing, 2007).

A general advantage of community dynamics models is the relative realistic representation of (above-ground) processes at a location. Furthermore, a positive aspect is the ease of estimating model parameters for a large number of species and circumstances. Community dynamics models, however, include less focus on ecosystem functioning and related carbon dynamics (although vegetation biomass is often estimated). These community dynamics models can, however, be linked to such models. The HPDM landscape model, for example, has been linked to the Century model to assess the consequences of land-use and land-cover changes for the C cycle in the Phoenix area (Wu *et al.*, 2003).

3.2.3 Biogeographical *models*

Biogeographical models have been developed to simulate the distribution of plant forms (e.g. single species, ecosystems) throughout the world under past, current, and future climate (Table 3-1). These models are mainly concerned with what an ecosystem could potentially become in a certain location rather than how it will grow. Nevertheless, the distribution is relevant for the terrestrial C cycle too because different ecosystems contain different C quantities and C dynamics are affected differently.

Early stage biogeographical models – like the Holdridge (Holdridge, 1967) and BIOME1 (Prentice *et al.*, 1992) models — link the distribution of ecosystems/biomes directly to climate variables (see review by Leemans *et al.*, 1996). Whereas the Holdrige model uses only two annual climate indices and considers ecosystems as homogenous entities, the BIOME1 model includes five climate variables, also reflecting differences in seasonality. Furthermore, BIOME1 considers ecosystems that are combinations of different plant life forms (so-called plant function types or PFTs) and include soil characteristics in the simulation of evapotranspiration. As such, this model includes important processes that define ecosystem distribution. BIOME1 has been used frequently over the past decades to assess the effects of climate change on the ecosystem distribution (for example, Prentice *et al.*, 1998; Beerling & Mayle, 2006, for the paleo-climate and Füssel *et al.*, 2003, for projected climate scenarios). Despite this variation among early-stage biogeographical models, all these models simulate the ecosystem distribution more-or-less statistically. Furthermore, the models assume an ecosystem to be in equilibrium and ignore competition between (groups of) plant species. These assumptions may be valid on long-term scales (e.g. centuries), but are less applicable under fast-changing conditions (Huntley *et al.*, 1997). Finally, in these early models there were no C-cycle processes included at all.

To overcome some of the shortcomings, biogeographical models became more process-based during the 1990s. Models like BIOME3 (Haxeltine & Prentice, 1996) or MAPSS (Neilson, 1993) project changes in vegetation distribution that are based on differences in functioning (i.e. productivity) of different plant types. As such, these models explicitly consider plant competition. The productivity is a function of climate, soil moisture availability (including different rooting depth), and radiation.

These more process-based biogeographical models can be seen as the first attempt towards the development of Dynamic Global Vegetation Models (DGVM, see below).

In summary, biogeographical models link climate and some local conditions to the broad ecosystem/ biome distribution across the world. They have been used in a variety of assessments to show important consequences of climate change, especially if a biome can be linked to biodiversity, for example (as seen in Hannah *et al.*, 1995) or the C cycle (e.g. Smith *et al.*, 1992; Van Minnen *et al.*, 1995). Furthermore, the structure of (early) biogeographical models is relatively simple, providing the possibility to incorporate them in combined models (see below) such as Integrated Assessment Frameworks (e.g. IMAGE2, section 3.4; and ICLIPS, Füssel *et al.*, 2003) or climate models (e.g. Claussen, 1994; Claussen, 1996). However, although there has been clear progress made in the biogeographical models towards the consideration of ecosystem functioning, the simulation of ecosystem structure in these models is still essentially static. Furthermore, temporal dynamics and geographical barriers (e.g. migration rates and mountains) are not included, which could have a considerable effect on the global C balance (Van Minnen *et al.*, 2000). Finally, biogeographical models simulate only the potential distribution of natural ecosystems. Overlays with land-use maps are required to depict the actual land cover throughout the world.

3.2.4 Biogeochemical models

The category of *biogeochemical models* consists of a broad range of models that all aim to evaluate the effects of environmental changes on the functioning of terrestrial ecosystems in terms of C pools and fluxes, water, and energy. These models have been applied to evaluate the consequences of such issues as air pollution (see review by Tiktak & Van Grinsven, 1995) and climate change (see reviews by Mohren *et al.*, 1997; Heinmann *et al.*, 1998; Cramer *et al.*, 1999).

Biogeochemical models are, in general, process-oriented, but do not incorporate many structural differences in vegetation. Furthermore, they generally assume a fixed geographical distribution of natural ecosystem types with fixed parameter settings for each of these types (Prentice *et al.*, 2000). By nature, biogeochemical models include full C cycles with a more detailed description of soil compartments and processes. Furthermore, some biogeochemical models also include a nutrient cycle.

Here, I distinguish three subtypes of biogeochemical models according to the target scale (section 3.3) involved (Table 3-1): (i) *Ecophysiology-based* deterministic models to assess the C dynamics from the stand/patch to the regional scale; (ii) C*anopy-based models*, simulating C dynamics on the regional to global scale, on the basis of radiation balances and using satellite information, and (iii) T*errestrial ecosystem models* (TEMs) simulating biogeochemical fluxes from the large regional scale (e.g. continents) up to the global scale.

Ecophysiology-based models are process-based models that simulate the dynamics of C and other compounds for individual trees or patches (Table 3-1) (Tiktak & Van Grinsven, 1995; Mohren *et al.*, 1997). This tree/patch information is then scaled up to the regional scale (e.g. Europe, Kramer *et al.*, 2002). Although the complexity varies even within this model type (see review by Sonntag, 1997), the models all estimate plant or patch growth as an outcome of C uptake by photosynthesis, C consumption through respiration and allocation, the conversion towards biomass, turnover, litter production, and soil decomposition. The C uptake in the course of a day is often estimated by using the CO_2 gradient between the atmosphere and leaf interior for a number of canopy layers and leaf ages (in the case of pre-annual vegetation). Nutrient content (if included) is used for estimating maintenance respiration. The allocation process is important because it determines the amount of C (and nutrients) available for the various plant compartments and – if included – non-structural reserves. Different approaches to the allocation process exist, varying from fixed, environment-independent rates up to mechanistic approaches, where allocation is a function of demand.

Canopy-based biogeochemical models simulate C uptake and plant growth, primarily based on radiation interception by the canopy. Reduction factors are used for non-optimal temperature conditions and shortage of water or nutrients. A direct effect of CO_2 has been added as multiplier. Two types of canopy-based models are distinguished (Goudriaan *et al.*, 1999): (i) models that simulate net primary productivity (NPP) on the canopy scale, based on the total radiation at the canopy and (ii) models that simulate C, energy and water fluxes for the individual leaves of plants, followed by integration across the canopy level. The latter models have various points in common with the aforementioned ecophysiology-based models and some of the managed ecosystem models. The real canopy models have links to the whole terrestrial ecosystem models (see below) and are applied from the regional up to the global scale.

The many different *Terrestrial Ecosystem Models (TEMs)* in existence (see review by Cramer *et al.*, 1999) all aim to simulate the exchange of C, water, and nutrients both within the terrestrial biosphere, and between the atmosphere and terrestrial biosphere on regional or global scales (Table 3-1). The major processes included are photosynthesis, respiration, evapotranspiration, nutrient and water uptake, and allocation to different plant compartments, litter production, soil decomposition, and often phenological development. Furthermore, TEMs often include aggregated classes of plant compartments due to their large-scale application.

TEMs differ with respect to the level of complexity. TEMs commenced development on climate change effects on the C dynamics in the 1970s, starting with the MIAMI model (Lieth, 1975). These early models (e.g. Emanuel *et al.*, 1984; Goudriaan & Ketner, 1984) included only a few major ecosystems, were not spatially explicit, and captured globally aggregated, highly parameterized, and regression-based biogeochemical C processes in ecosystems. Ecosystem growth –often expressed as Net

Primary Production, NPP– has, for example, often been simply based on vegetation characteristics and climate conditions.

Somewhat improved TEMs have been implemented on geographical grids, which characterize local heterogeneity in environmental factors. Over the past decade, TEMs took on more mechanistic relationships to assess carbon, water and nutrient fluxes on different scales and resolutions (e.g. the Bethy model, Knorr & Heinmann, 2001 or the Hybrid model, Friend *et al.*, 1997). This change was needed because the use of empirical relationships has proven to be difficult under fast changing environmental conditions (Kaduk & Heinman, 1996). The more detailed TEMs, for example, distinguish between Gross Primary Production (GPP) and autotrophic respiration, both affected by vegetation characteristics and environmental conditions. NPP is then estimated as the difference between these two fluxes. GPP is a function of solar radiation, daily climate, atmospheric CO_2 concentration, soil conditions (mainly soil water content), and sometimes nitrogen availability (e.g. in the Hybrid model). A strong feature of these models is the explicit consideration of feedbacks and interactions within the biosphere (e.g. through leaf shading), and between the biosphere and climate system.

An advantage of many biogeochemical models is their connection to the “real world”. Ecophysiology-based models are developed for the patch level where observations exist. Canopy-based models often can be driven by remote sensing data, improving the validation potential. Furthermore, a large variation of TEMs has been developed in the meantime, enabling model intercomparisons. Another advantage of most TEMs is that they include processes at a level of comprehensiveness that enables a link between these models and climate models (e.g. Foley *et al.*, 1998; Friend *et al.*, 2007). This happens at the cost of computational time and large data demand. Furthermore, as already mentioned, most biogeochemical models do not incorporate much variation in vegetation structure and assume a fixed geographical ecosystem distribution. Likewise, biogeochemical models are still very crude with respect to: (i) forest management; (ii) C cycling in agricultural areas and wetlands; (iii) frozen soil C dynamics; (iv) the effects of land-use change and fires and (v) effects on biodiversity (Denman *et al.*, 2007).

3.2.5 Biogeophysical models

Biogeophysical models have often been developed as the land-surface component of global circulation models (GCMs) and regional climate models (RCMs). The models simulate the exchange of energy, water, and carbon between land surface and atmosphere (Table 3-1). As the models have been explicitly developed to be integrated in GCMs and RCMs, biogeophysical models simulate these fluxes on the regional or global scale (for example, because of the coarse resolution of GCMs). However, some of these models can also run off-line, simulating more local/patch fluxes.

Biogeophysical models estimate the physical interaction between ecosystems and atmosphere at a high level of detail. The main processes are the uptake of CO_2 through stomata, and the loss of water through stomata (=transpiration), canopy, and soil (=evaporation). With respect to ecosystem dynamics, one of the most important drivers is FPAR (i.e. Fraction of Photosynthetically Active Radiation), which can be easily derived from satellite data. The amount of radiation captured at different leaves within canopies (and derived from FPAR) determines the leaf gross photosynthesis, together with some leaf characteristics and moisture availability. The photosynthesis and conductance (from stomata and leaves) are explicitly connected, determining the CO_2 uptake and water loss. As feedback, leaf conductance is also determined by atmospheric CO_2 concentration and the water gradient between atmosphere and stomata (determined by relative humidity). The net leaf photosynthesis is estimated by subtracting leaf respiration, which is a function of leaf characteristics. The subsequent step is integrating the leaf outcomes over a canopy, stand and even region. This has, for example been done through a relationship between FPAR and the leaf area index (LAI) of trees, or even region (see Sellers *et al.*, 1996). LAI can, in turn, be easily linked to NPP (also done in other model types like BIOME3, Haxeltine & Prentice, 1996). A similar detailed approach was implemented in biogeophysical models to simulate the water flux from soils into the atmosphere (i.e. evaporation) (Henderson-Sellers & McGuffie (1995); Sellers *et al.*, 1996).

An advantage of biogeophysical models is their accuracy and low temporal resolution, enabling them to be linked to climate models. Furthermore, important drivers such as FPAR can be easily derived from satellite data, although the models have a large data requirement (due to the large complexity and comprehensiveness). On the other hand, the focus of biogeophysical models is on the carbon, water, and energy exchange between atmosphere and biosphere. Less attention is given to fluxes and pools within ecosystems (i.e. between vegetation and soil), which makes them less applicable to simulate the terrestrial C cycle.

3.2.6 Models combining principles

Models have been coupled in different ways (i.e. soft-linked up to fill integration) over the past decades to simultaneously simulate ecosystem composition/structure and functioning. The different model types were coupled/integrated on the basis of different objectives and applications (Table 3-1).

First, over the past decade, *Dynamic Global Vegetation Models* (DGVMs) have been developed as advanced terrestrial C-cycle models (see review by Cramer *et al.*, 2001). DGVMs integrate elements from biogeographical, biogeochemical and biogeophysical models (Table 3-1). These models explicitly consider C dynamics under non-equilibrium conditions, i.e. allowing transient changes in ecosystem structure and composition, while considering establishment, succession, and disturbance. Vegetation dynamic principles – such as competition between plants for light and water, mortality, and human and natural disturbances – are generally derived from patch models. The C dynamics are simulated in a way that is comparable to the approaches used in biogeochemical models (Table 3-2**).** DGVMs vary in complexity, from reduced-form types (e.g. VECODE, Brovkin *et al.*) to very detailed models (e.g. HYBRID, Friend *et al.*, 1997) or SDGVM, Woodward & Lomas , 2004). The time step used, for example, varies from 1 hour to 1 year (Cramer *et al.*, 2001). Furthermore, DGVMs differ with respect to chemical elements considered. Whereas all DGVMs include carbon and water, only a few consider nitrogen, varying from a fixed C:N ratio to implicit N cycle. Because of the integration, and their complexity, DGVMs can be currently seen as the most comprehensive terrestrial C-cycle models. Nevertheless, DGVMs are still crude with respect to (i) ecosystem management and its effect on the C cycle; (ii) the C cycling in wetlands and perma-frost areas and (iii) effects on biodiversity (Denman *et al.*, 2007). Furthermore, data demand and computing requirement have increased exponentially with the development of these models.

Second, biogeochemical models (especially TEMs) and DGVMs become more and more coupled to climate and land-use models (Table 3-1 VI-II). Both links aim at a better representation of the terrestrial ecosystems in the global climate system.

Coupled climate–DGVMs aim at a more accurate understanding of the regional land–atmosphere interactions – including feedbacks – between ecosystems and atmosphere (Table 3-1) (see reviews by Berthelot *et al.*, 2005); Friedlingstein *et al.*, 2006 and Brovkin *et al.*, 2006). In general, special attention is given to changes in ecosystem distribution and, in particular, structure. Whereas climate models in general use an equilibrium vegetation pattern that remains constant in time, the coupled models now include transient vegetation changes and their consequences for the land-surface physics and processes. These changes have an effect on such factors as vegetation height, leaf area index (LAI), and crown cover characteristics like surface roughness. Such factors are relevant in the climate models to simulate the local/regional climate because of the effects on radiation balance (i.e. albedo), transpiration and rainfall interception, and C uptake. These coupled models still work with crude assumptions pertaining to: (i) ecosystem management; (ii) the C cycle in certain areas, and (iii) the effect of land-use changes, although this challenge has been taken up in some recent model development work (e.g. Schaeffer *et al.*, 2006).

Different types of terrestrial C-cycle models have also been linked to *land-use models* in order to compare the effects of climate change with land-use change on the terrestrial C cycle. Sitch *et al.* (2005) and Friend *et al.* (2007), for example, used external information on land use in their DGVMs, whereas Gervoisa *et al.* integrated the ORCHIDEE DGVM with the STICS crop model.

A final subtype of combined models consists of Integrated Assessment Models (IA). Here the C cycle and ecosystem distribution are part of a large modeling framework (Table 3-1). These frameworks cover the entire chain from human activities – including economics – to environmental impacts like climate change, including feedbacks. IA models have mainly been developed for policy support. Models like IMAGE-2 (this thesis) and ICLIPS (Füssel *et al.*, 2003) have been developed, for example, to provide insights into the long-term build-up of greenhouse gases in the atmosphere. Terrestrial ecosystems play an important role in the issue of future greenhouse gas concentrations, because the ecosystem behavior determines what will happen with the current terrestrial sink and how C sequestration can be maintained or enhanced. With policy support being the main objective – with specific requirements such as long time horizons, large-scale application and multiple scenario analysis – IA models generally include processes in a reduced form (see, for example, IMAGE 2 in section 3.4). Due to the reduced form representation of processes, IA models have their limitations (see section 3.4). However, modules/processes can be easily replaced so as to perform multiple experiments and assess consequences of uncertainties (see chapter 4). Furthermore, IA models include a full integration of the earth system from human activities to impacts (e.g. relevant feedbacks). This provides the possibility to produce policy-relevant indicators (e.g. atmospheric CO_2 concentration and global average temperature).

Table 3-1 Terrestrial C-cycle model categories and underlying model types

Model types	Examples	Main objectives	Spatial scale	Time Step	Compre-hensiveness	Reviewed by
I Managed terrestrial ecosystem models						
I.1Crop & grassland models	CERES (Rosenzweig *et al.*, 1999) Sirius (Lawless *et al.*, 2005) SUCROS (Van Laar *et al.*, 1992) GEM2 (Hunt *et al.*, 1991)	-Productivity of crops and grassland species as influenced by environmental conditions	Patch to region	Day to year	++	Jamieson *et al.*, 1998 Tubiello & Ewert, 2002 Campbell *et al.*, 1997
I.2 Forest yield models	HOPSY (Hinssen, 1994) STEMS	-Forest structure and productivity as influenced by site conditions	Patch	Day to year	+/++	Mohren & Burkhart, 1994 Mohren *et al.*, 1997 Vanclay & Skovsgaard, 1997
II Community dynamics models						
II.1.Gap/patch models	ForClim (Bugmann *et al.*, 1997) Foret (Shugart *et al.*, 1981) Forska (Leemans; Formix (Huth, 2000) Jabowa (Botkin, 1972) LINKAGES (Post & Pastor, 1996)	-Patch structure and composition through the simulation of the establishment, growth and mortality of individual plants	Patch to region	Week to year	++	Martin, 1993 Mohren & Burkhart, 1994 Bugmann *et al.*, 1996 Shugart & Smith, 1996
II.2 Landscape models	ForelL (Busing, 2007) Logofet & Lesnaya, 2000 MUSE (Gignoux, 1997) FATE Moore, 1993	-Landscape dynamics, considering interactions of spatial elements. Links to II.1	Region	Year	++	Balzter, 2000 Lee *et al.*, 2003
III Biogeography models						
III.1 Equilibrium ecosystem models	BIOME1 (Prentice *et al.*, 1992) EuroMove (Bakkenes *et al.*, 2006) Holdridge (Emanuel *et al.*, 1985)	-Potential distribution of natural plant life forms, depending on climate and resource constraints.	Region to globe	Month-year	+	Leemans *et al.*, 1996
III.2 Process-based models	BIOME3 (Haxeltine & Prentice, 1996 Doly (Woodward *et al.*, 1995) MAPSS (Neilson, 1993)	-The same but more process & accounting for plant competition	Region to globe	Month	++	Neilson & Running, 1996)
IV Biogeochemistry models						
IV.1 Ecophysiology-based models	ForGro (Kramer & Mohren) SoilVeg (Van Heerden *et al.*, 1995) Treedyn Sonntag, 1998)	-C balance and growth, phenological stages and soil dynamics using physiological principles	Patch to region	Day	+++	Tiktak & Van Grinsven, 1995 Mohren *et al.*, 1997 Kramer *et al.*, 2002

IV.2 Canopy based models	BIOME-BGC Running & Hunt, 1993 CASA (Potter *et al.*, 1999) SDBM (Knorr & Heiman, 1995)	-Ecosystem growth-based on radiation interception	Patch to globe	Day	+++	
IV.3 Terrestrial Ecosystem Models (TEM)	Bethy (Knorr & Heinmann, 2001) BIOME-BGC (Neilson & Running, 1996) CENTURY (Parton *et al.*, 1994) FBM (Kohlmaier *et al.*, 1997) HRBM Kaduk & Heinman, 1996) Hybrid (Friend *et al.*, 1997) MAPPS (Neilson & Drapek SLAVE (Friedlingstein *et al.*, 1995 TEM (Tian *et al.*, 1999)	-Large scale exchange of C and water between atmosphere and biosphere, in response to changes in environmental conditions	Region to globe	Day to year	+++	Heinmann *et al.*, 1998; Cramer *et al.*, 1999)
V Biogeophysical models	SiB2 Sellers *et al.* BATS (Henderson-Sellers & McGuffie, 1995)	-Coupled simulation of the energy, water and C exchange between atmosphere and biosphere over large regions	(patch), Region to globe	Minutes to day	+++	
VI Models combining different characteristics *VI.1 DGVMs*	IBIS Kucharik *et al.*, 2000 LPJ (Sitch *et al.*, 2003 ORCHIDEE (Krinner *et al.*, 2005 SDGVM (Woodward & Lomas, 2004 SEIB (Sato *et al.*, 2007)	-Impacts of environmental changes on ecosystem functioning and disturbances, by considering the interaction of energy, water and C cycle	Globe	Day to month	++++	Cramer *et al.*, 2001 Friend *et al.*, 2007
VI.2 Coupled climate–biosphere models	CLIMBER-LPJ Brovkin *et al.*, 2006 ; Sitch *et al.*, 2005 FOAM-LPJ (Gallimore *et al.*, 2005) HadCM3LC (Cox *et al.*, 2000) Speedy Schaeffer *et al.*, 2006	-Changes in ecosystem cover and structure for accurate climate modeling	Globe	Minutes to month	++++	Berthelot *et al.*, 2005 Friedlingstein *et al.* , 2006
VI.3 Integrated Assessment models (IA)	IMAGE 2 (Van Minnen *et al.*, 2006) ICLIPS (Füssel *et al.*, 2003) EXPECT (Bakema *et al.*, 1994)	-Long-term C-cycle/ ecosystem growth as part of a model chain from human activities to environmental effects, with policy support as aim	Region to globe	Month to year	++	

Table 3-2 C-cycle related characteristics of considered model types.

Model type	*Used approach for ecosystem functioning & composition*	*Main input variables*	*Output related to C cycle*	*Concepts used for IMAGE-2 C-cycle model*
I Managed terrestrial ecosystem models *I.1 Crop & grassland models*	CO_2 assimilation, plant respiration and biomass increases through the growing season	Climate[3] Water & nutrient availability Atmospheric CO_2 Reducing factors (e.g. pests) Management regimes	Biomass & food production	Growth rates
I.2 Forest yield models	Empirical relation hips between tree type, age and site conditions	Tree species Site conditions/site index	Tree height & density m^3 wood	Tree growth rates after harvest
II Community dynamic models *II.1 Gap/patch models*	Plant establishment, growth (related to diameter development) and mortality are all functions of environmental constraints/ stress. Potential diameter increase is a pre-described function, where the increment is based on the current size relative to its maximum	Light/radiation Climate Soil conditions (e.g. water, nutrient)	Plant-species composition Forest structure & development (e.g. height) m^3 biomass production	Competition & succession, resistance of species under climatic changes, tree growth rate
II.2 Landscape models	The same, although often less detailed or coarser resolution	Same	Landscape/ecosystem structure Land-use patterns m^3 biomass production	Spatially connected land-use modeling Parameterization for migration routine
III Biogeography models *III.1 Equilibrium ecosystem models*	Ecosystem composition= f(climate, soil moisture, dominance index)	Climate Atmosph.CO_2 Soil type	Potential vegetation distribution	Vegetation distribution under climate change
III.2 Process bases models	Ecosystem composition= f(NPP, soil moisture, climate) NPP= f(LAI, climate, CO_2)	Climate Atmosph.CO_2 Soil type	Potential vegetation distribution Long-term NPP and plant characteristics	Same
IV Biogeochemistry models *IV.1 Ecophysiology-based models*	Growth = f(GPP, respiration, nutrient, stress) GPP = f(CO_2 gradient, light, moisture, T) Respiration = f(T, nutrient content)	Climate (often incl. wind & hum.) CO_2 concentration Radiation (Pollution/deposition) Species composition/ distribution	Local and regional Phenology C uptake & growth Biomass (distribution)	

IV.2 Canopy based	C uptake and plant growth is primary based on radiation interception. Reduction factors are used for non-optimal temperature conditions, and shortage of water or nutrients. CO2 fertilization as multiplier.	Radiation Climate Atmosph.CO_2 Land cover & use Soil type, N content & texture	Short & long-term C (and nutrient) dynamics	
IV.3 Terrestrial Ecosystem Models (TEM)	$NPP = GPP - R_a$ && $NEP=NPP - R_h$ NPP, GPP and Respiration (R_a & R_h) are estimated by different levels of complexity	Climate Atmospheric CO_2 Land cover & use Soil characteristics (N deposition)	C (and nutrient) dynamics in vegetation and soil C pools Ecosystem characteristic	C-cycle processes: NPP, soil respiration, feedbacks Parameter setting & validation
V Biogeophysical models	Leaf photosynthesis = gross photosynthesis– leaf respiration Gross photosynthesis = f (FPAR, T, leaf characteristics, water & CO_2 gradient) Leaf Respiration = f (leaf characteristics, T)	Radiation Climate (incl. wind & humidity, vapor pressure) Atmospheric CO_2 gradient Actual vegetation map (determining boundary layer) Local conditions (e.g. soil characteristics)	Canopy structure Photosynthesis CO_2 uptake and transpiration albedo	
VI Models combining different characteristics *VI.1 DGVMs*	Ecosystem composition= f(NPP, soil moisture, climate) NPP = GPP – Respiration GPP = f(climate, CO_2, radiation, water)	Climate (often incl. humidity and wind) Atmospheric CO_2 concentration Radiation Local conditions (e.g. soil)	Short & long-term C dynamics Vegetation distribution & structure, considering environmental changes and disturbances	LPJ currently implemented in IMAGE (version 3)
VI.2 Coupled climate- biosphere models	Similar as III.2, or VI.1	Climate (often incl. humidity and wind) Atmospheric CO_2 concentration Radiation Local conditions (e.g. soil)	Long-term C dynamics Vegetation distribution, considering certain special links (e.g. climate, land use).	
VI.3 Integrated Assessment models (IA)	Similar to IV.3	Climate CO_2 concentration Radiation Local conditions (e.g. soil)	Long-term C dynamics Vegetation distribution, considering certain climate & land use	

---

[3] If not specified explicitly, climate means monthly temperature, precipitation and cloudiness.

3.3 Scales and scaling in terrestrial C-cycle modeling

Results and conclusions for the past, current, and future terrestrial C cycle obtained on one scale are not automatically valid on another scale (MA, 2005). Local patterns, anomalies, and exceedances of thresholds, observed, for example, on a fine scale may disappear if the results are presented on a coarse scale. There are three reasons why scales and scaling are important in terrestrial C-cycle modeling. First, the terrestrial C cycle fluctuates on all temporal and spatial scales, depending on numerous processes. The relevance of the processes varies between temporal (seconds to decades), spatial (landscapes to biomes) and organizational (leaf, individuals, communities) scales (Cash *et al.*, 2006). Climate change is, for example, a main driver of vast changes in world ecosystem behavior and hence in the provision of large-scale ecosystem services (MA, 2005), whereas differences in soil conditions drive more regional variations (De Vries *et al.*, 2006). Second, interactions take place across different time and spatial scales, so that outcomes on a specific scale are often influenced by (ecological) factors of different scales (Baldocchi, 1993; Cash *et al.*, 2006). For example, global climate change may result in a regional loss of forest cover, which, in turn, increases the flood risk along a local river (MA, 2005). Final, environmental problems take on regional (e.g. air pollution) and global (e.g. climate change) dimensions (Figure 3-2), whereas the knowledge of the physiological and biogeographical processes involved becomes more detailed (Levin, 1992; Jenerette & Wu, 2000). This is especially relevant for modeling exercises where processes, data, etc. from different scales have been integrated (Jenerette & Wu, 2000).

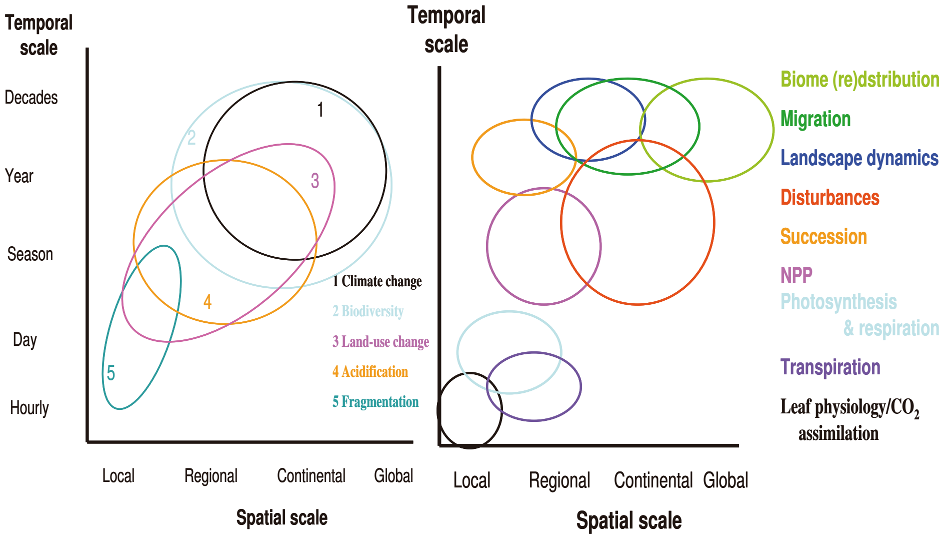


Figure 3-2 **Temporal and spatial domain of environmental concerns (left) and C-cycle dynamics (right).**

The objective of this section is to outline different aspects of scales and scaling. This includes an enumeration of existing definitions and a description of different scaling concepts. Parts of the scaling concepts are taken up later in this chapter in the description of the IMAGE-2 C-cycle model.

3.3.1 Scales

“Scale” refers to the spatial or temporal dimension of an object or process (Bailey, 1996; Gibson *et al.*, 2000; Jenerette & Wu, 2000; Cash *et al.*, 2006). Temporal and spatial scales are correlated (Figure 3-2) and often referred to as the *scale domain* of a process or system (MA, 2005). Three types of scales have been distinguished in ecological studies (Baldocchi, 1993; Jenerette & Wu, 2000; Lam, 2004): The target scale or extent, the grain or determinational scale, and the operational scale.

The *target scale or extent* is the spatial or temporal scope of a study, i.e. the size of the study area or the duration time under consideration (Baldocchi, 1993; Dumont, 2007). It is important to define in any study the target scale because it determines the processes that should be considered and how these should be described (Field, 1991, Baldocchi, 1993; Bugmann & Martin, 1995). As already mentioned, processes can be important on one scale, but unimportant on others (Jenerette & Wu, 2000; Dumont, 2007). A main determinant of the target scale is the objective of the study (Baldocchi & Harley, 1995; Bouwman *et al.*, 1996). This is important because increasing detail generally leads to a more accurate understanding (Verboom, 1996; Torfs, 1996). But is this increasing detail – including higher data demand and increasing computational expanses – needed in the context of the objectives of the study?

The *grain or determinational scale* refers to the spatial and temporal resolution of a study, i.e. frequency and precision of observations, or the smallest time step and spatial unit that can be distinguished. For example, many global C-cycle models include a 0.5° longitude x 0.5° latitude resolution. The heterogeneity of a system (see below) is one of the main drivers of the grain.

The *operational scale* of (ecological) information refers to the spatial and temporal scales and the organizational aggregation at which processes operate in the environment (Lam, 2004). Ecosystem growth, for example, can be simulated by considering photosynthesis of leaves or canopies and with a temporal scale of minutes up to hours. Alternatively, ecosystem growth can be estimated by simulating monthly and annual Net Primary Production (NPP). Likewise, ecosystem composition can be assessed by considering individual species or aggregated plant functional types (PFTs). The complexity of the underlying system and the research objectives are the main drivers of the operational scale (Jarvis, 1995; Leuning *et al.*, 1995).

It is important to compare the operational scale of relevant processes with the target scale/extent of a study. If, for example, a study covers a smaller or shorter extent than the operational scale of relevant processes, the study will not adequately capture variability and dynamics associated with long-term cycles such as climatic or economic trends. Hence, the outcome of the processes will not be seen on the target scale. On the contrary, if relevant processes are complex (i.e. the operational scale is too small and/or reacts too fast), the outcome of the processes may appear as anything but background noise on the target scale (O'Neill, 1988; Jarvis, 1995; Leuning *et al.*, 1995).

Also the grain/determinational scale and target scale/extent are linked, i.e. they determine the scale boundaries of an assessment. The upper limit of data resolution is set by the extent, and the lower limit by the grain. In other words nobody can detect patterns finer than the grain or coarser than the extent.

Related to the different types of scales is the *heterogeneity* of a system. Heterogeneity is defined as the variation among the units in a system (King, 1991; Levin, 1993). I define *internal* and *external* (or horizontal) heterogeneity. The former refers to the grain. External heterogeneity describes the variation among the units on the target scale. When the grain is kept constant, increasing the extent will result in larger external heterogeneity, since systems, state variables, and processes become more complex. For example, the diversity of soil types or the number plant species is normally larger at a regional level than in individual forest stands. When the extent of a study is held constant, an increasing grain decreases the external heterogeneity, i.e. processes or systems become more aggregated.

3.3.2 Scaling concepts

In order to exchange information across scales, scaling concepts are needed (Jarvis, 1995; Dumont, 2007). For example, how can information derived from field experiments be accurately used in modeling exercises that assess climate change consequences on regional, continental, or global scales? I define scaling as *the manipulation of information, derived on one scale to obtain information on another scale* (following Norman, 1993 and Jarvis, 1995). In the context of ecology, "information" refers to a particular biosystem (e.g. an individual plant or entire ecosystem), state variable (e.g. biomass) or process (e.g. photosynthesis). Here I describe different scaling concepts. The concepts can be grouped into *scaling-up* and *scaling-down*.

Scaling-down
Scaling-down consists essentially of deriving fine-scale information by studying a defined system or process on a coarse scale, and breaking it into parts by using knowledge about the coarse- and fine-scale properties (MA, 2005; Dumont, 2007). A relatively simple scaling-down approach, frequently used in simulation models, is interpolation. More complex approaches use relationships based either on models or empirical data (Payn *et al.*, 2000). In the end, scaling-down leads to a larger variety within a system, implying a mosaic of patches, and thus a larger internal heterogeneity

(Jarvis, 1995). The problem is the increasing complexity associated with the increasing internal heterogeneity. Delving too deep into small and short scales could result in inadequate results. Furthermore, data availability could limit the determination of the relationships mentioned.

Scaling-up

Scaling-up is the assemblage of information on the fine (temporal and spatial) scale to use it on coarser scales (Jarvis, 1995; Dumont, 2007). I define four different scaling-up concepts (Figure 3-3), combining the concepts of Norman (1993), Jarvis (1995) and Goudriaan (1996). These are: i) summation or adding; ii) averaging; iii) aggregation, and iv) enlarging. These concepts are described below in more detail, showing that the most suitable concept depends on the scale distance that has to be bridged, and the type of information (i.e. system, state variable, or process) that needs to be scaled. I illustrate the description by using the C sequestration potential in Dutch forests as an example, assuming that the Netherlands consists of only four tree species (e.g. pine, fir, oak and beech). Stand information on these species is scaled up to the country level in order to estimate the national C sequestration potential. An important feature of all scaling-up concepts, except summation, is that they lead to an intermediate step in which the information is combined into new, reduced-form units/grains. These units have to be blown-up (or extrapolated) to information on the target scale (Goudriaan, 1996).

Note that scaling-up often requires generalizations and simplifications at a certain stage, because of the increasing external heterogeneity (i.e. larger diversity and variation among units) and systems become too complex to maintain all the detail. Generalization should be applied in such a way that it leads to a collection of cases (e.g. ecosystems) whose behavior is regular enough to allow them (Levin, 1993). Different types of generalizations exist. *System generalization* is the clustering of certain biosystems into a larger group using common (biological) characteristics, like phenological characteristics. Multiple classification schemes, for example, have been developed that are useful to aggregate individual plant species (see e.g. Leemans, 1994). *Spatial generalization* results in a more general categorization of the spatial units. Individual forest stands, for example, can be grouped into forested areas, using simple age class and species characteristics. This has, for example, been used in the Canadian Budget Model (CBM, Kurz *et al.*, 1995). Spatial generalization is applicable to different frameworks where spatial units can be distinguished (e.g. modeling, GIS). *Technical* and *process generalization* are more related to the development of simulation models. *Technical generalization* is the change to a different modeling concept, like a change from process-oriented modeling towards input–output modeling. *Process generalization* is the simplification or different formulation of processes by introducing certain correlations (e.g. a change from detailed stomata uptake of atmospheric compounds to only dose—effect relationships). These generalization approaches have been used differently in the scaling-up concepts.

Summation or adding is based on the “more of the same” concept, where information is measured on a detailed scale and then summed up to the target scale (Figure 3-3a). An example using an adding approach is seen in the canopy conductance as the sum of the individual stomata conductance (e.g. McNaughton, 1994). In my example of C sequestration in Dutch forests, summation would consist of summing up the C sequestration of the individual pine, fir, oak, and beech forest stands across the country in order to estimate the national C sequestration potential. The summation/adding concept is characterized by the same level of detail on the coarser scale (hence with a limited generalization and simplification), an independency of all components, and an ignorance of feedbacks and interactions on the coarser scale. These characteristics, in turn, limit the potential use of the approach. Large-scale variation is difficult or even impossible to handle, caused by the increasing number of processes and individuals (i.e. increasing external heterogeneity), and the existence of interactions and feedbacks on the coarser scale (King, 1991; Jarvis, 1995).

The basic principle of the *averaging* concept is that information on a coarser scale is derived on the basis of calculated averages of relevant information that have been estimated on the finer scale (Figure 3-3b). This can be achieved by either normal or weighted averaging on the fine scale. The new groups can then be applied as a base for further up-scaling. Applying the averaging concept in my example implies that the C sequestration potential in Dutch forests would be based on using species-specific yield tables across the country in combination with a C-cycle model. The tables are based on averaging the biomass increase as observed in some forest stands. In the end, the national C sequestration is defined by summing up the total C sequestration of the four species. Another example of the use of the averaging concept is the “big leaf” model, which simulates transpiration at a stand level, based on averaging leaf processes like stomata exchange (Lloyd *et al.*, 1995; DePury & Ceulemans, 1997). The averaging approach results in the loss of the variability between the individual components. Applying the averaging concept results in generalized processes and combinations of state variables (e.g. only two heights within a canopy). The concept is less applicable to scale-up species/ecosystems, because they can not be described by numbers. A disadvantage of the concept is its limited applicability if the complexity of a system considerably increases as part of the change in scale. This will result in an increase of the variation among the samples.

A*ggregation* (Figure 3-3c) consists of combining individual elements into new, indivisible classes. It requires similarities between the elements. An example is the grouping of individual plant categories into so-called plant function types (PFTs), as used in many terrestrial-ecosystem and C-cycle models (e.g. Prentice *et al.*, 1992; Sitch *et al.*, 2003; Picard *et al.*, 2005). Another example is the use of stand variable objects (SVO) in the Canadian Carbon Budget Model (Kurz *et al.*, 1992; Samson *et al.*, 1995), where ecosystems are aggregated on the basis of characteristics like age and phenology. In my example, aggregation would consist of defining new categories of coniferous (all pine and fir information) and deciduous (all oak and beech information) forests.

The second step defines the C sequestration of these new categories, often based on concepts different than the previous concepts due to large-scale application (e.g. net primary productivity instead of photosynthesis). The national C sequestration would then be based on summing up the C sequestration of the two classes. An advantage of the aggregation concept is that the new categories consist of more elements, often implying larger data availability. Note that in contrast to the previous two concepts, where the individual elements remained distinguishable, aggregation leads to a new set of classes, each having an unknown number of objects. Because it is impossible to return back to the detailed information, it is important to define, at an early stage, the minimum amount of detail required on the coarser scale. Another difference with the previous concepts is that the interaction and variability between the individual elements can be maintained (e.g. feedback factors between atmosphere and biosphere, and spatial variability within a forest stand) (Lischke *et al.*, 1998). Because of the preservation of interactions, the aggregation concept is very useful for bridging relatively large-scale differences. Aggregation becomes a problem if the complexity increases substantially in space and/or time, since this will limit the possibilities of grouping classes together into larger clusters. As shown by the examples, the aggregation concept is associated with generalizing systems (e.g. the PFTs), processes (e.g. NPP versus photosynthesis), and spatial units.

In the "*enlarging*" or *"representative sample"* (Figure 3-3d) one of the elements on the fine scale is assumed to be representative on the coarse scale. Differences between the original elements can be recognized, but are ignored on the coarse scale. The method is widely used under conditions where the information can not be split or combined without losing particular characteristics and where certain systems are used as indicators for certain areas and/or conditions (Jarvis, 1995). Because one element is selected, enlarging results in a generalization of a system, process, and spatial unit. In the example of the C sequestration in the Netherlands, one out of the four tree species is first selected. This because, for example, it is the most common species, or has the largest data availability or policy interest. In the second step, information on this species (especially its C sequestration) is used to estimate the national C sequestration potential. The enlarging concept has been used by Levin (1992), for example, in assessing large-scale environmental effects based on analogies to smaller scales. The advantage of enlarging is its simplicity, while the internal variability is kept constant. A disadvantage is that the enlarging does not account for an increase in external heterogeneity. Therefore it can lead to a less realistic representation of ecosystems. This is, however, often less relevant in, for example, many policy assessments, where indicators are selected to evaluate the consequences of different policy scenarios. Indicators can be particular processes (growth reduction of agricultural crops in relation to climate change), state variables (e.g. critical N concentration in leaves in the evaluation of air pollution) or systems (the abundance of Viola calaminaria as an indicator of soil contamination). Thus, although enlarging is a relatively simple concept, it is suitable to scaling all three types of information.

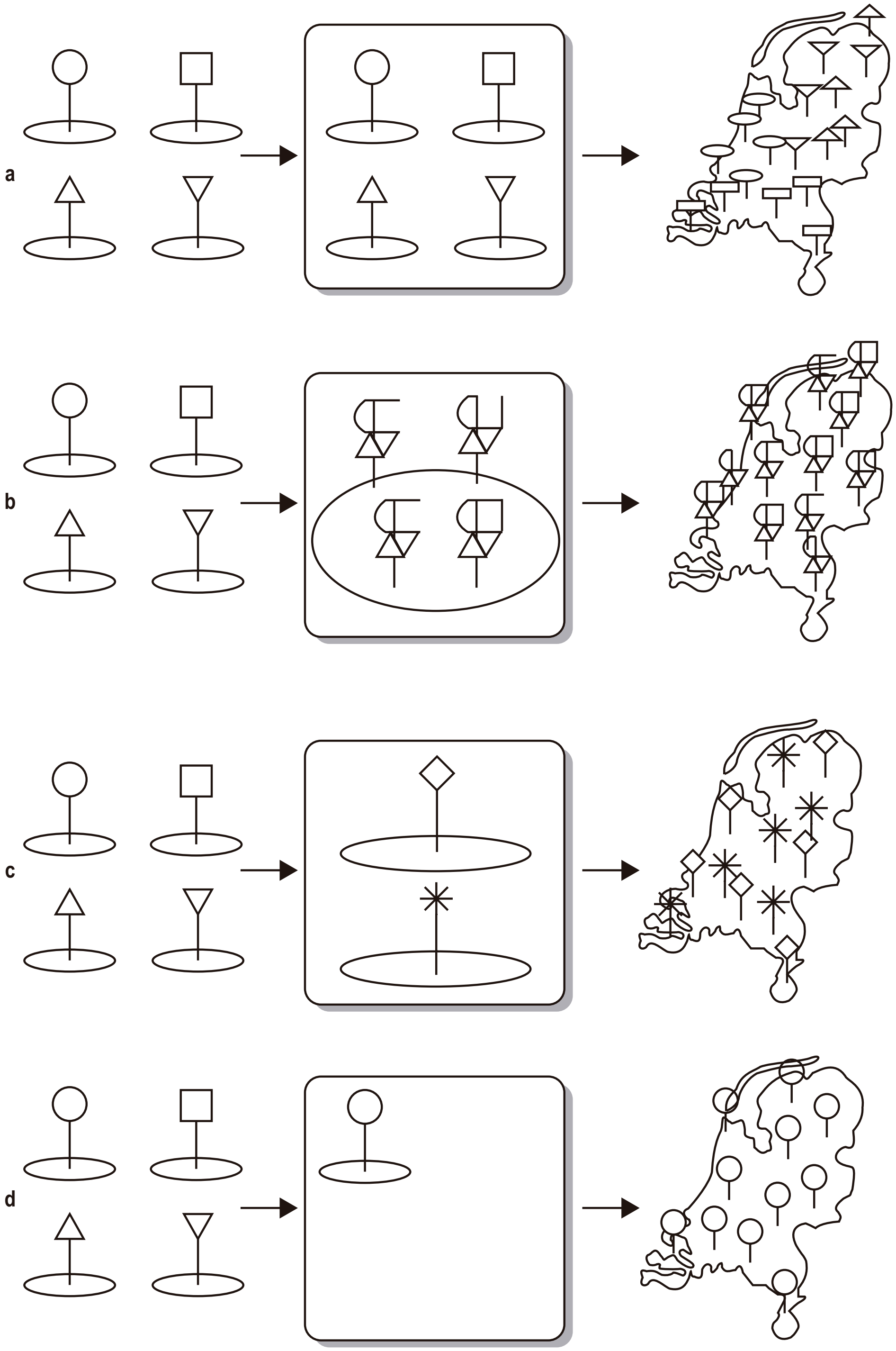


Figure 3-3 **Illustration of the four scaling-up concepts: a - summation; b - averaging; c - aggregation and d- enlarging.**

3.4 The IMAGE-2 terrestrial C-cycle model

3.4.1 Overview

In this section I describe the terrestrial C-cycle model of IMAGE 2 (Box 3.1). As part of this modeling framework, the terrestrial C-cycle model simulates the C fluxes between the terrestrial biosphere and the atmosphere, and within the terrestrial biosphere. The biosphere is that part of the terrestrial earth within which life occurs, and where biotic processes in turn alter or transform (http://nl.wikipedia.org/wiki/Biosfeer). The fluxes are the result of land cover, various environmental conditions (climate, soil, atmospheric CO_2), natural processes (i.e. migration), and land-use changes. All these factors are dynamically integrated. The resulting C pools and fluxes are used by the ocean and atmosphere model of IMAGE 2 to project changes in atmospheric CO_2 concentration and policy-related parts of IMAGE 2 that simulate, for example, the growth of bioenergy crops as well as C storage in C plantations.

Box 3.1 The IMAGE-2 model

IMAGE 2 (Integrated Model to Assess the Global Environment) is a multidisciplinary Integrated Assessment Model (IA) of intermediate complexity (Alcamo *et al.*, 1998; IMAGE team, 2001; MNP, 2006). Compared to simpler models, IMAGE 2 is geographically explicit and process-based (e.g. includes biochemical and biogeographical processes in its C-cycle model) and includes numerous interactions and feedbacks (e.g. between terrestrial C-cycle and land-use model). In comparison to more complex models, various simplifications have been implemented in IMAGE 2 with respect to processes, scales, etc. The overall design of IMAGE 2 is driven by its general objectives to explore the long-term dynamics of global environmental change to support both science and policy. IMAGE 2 has been applied to past, current, and future environmental and social trends.

IMAGE 2 consists of three major parts (Figure 3-4): a socio-economic system with basic driving forces (SES), an earth system (ES), and an impact system (IS). Interactions and feedbacks are explicitly included. The basic driving forces in SES – demography (Hilderink, 2006), energy supply and demand (Van Vuuren *et al.*, 2006), world economy (CPB, 1999), and agricultural economy and trade (Eickhout *et al.*, 2006) – interact with ES through land use and land-use emissions. In ES the concentration of greenhouse gases (e.g. CO_2), some air pollutants (e.g. SO_2) in the atmosphere and, subsequently, the climate are computed by aggregating the land-use and energy-related emissions and subtracting the oceanic and terrestrial C uptake (Eickhout *et al.*, 2004). Climate change alters the distribution and productivity of ecosystems and agriculture, which affects the terrestrial C cycle. Furthermore, changes in climate, land cover, and land use are also used by the IS to compute environmental impacts in a broader sustainability context (i.e. land degradation, water, and biodiversity).

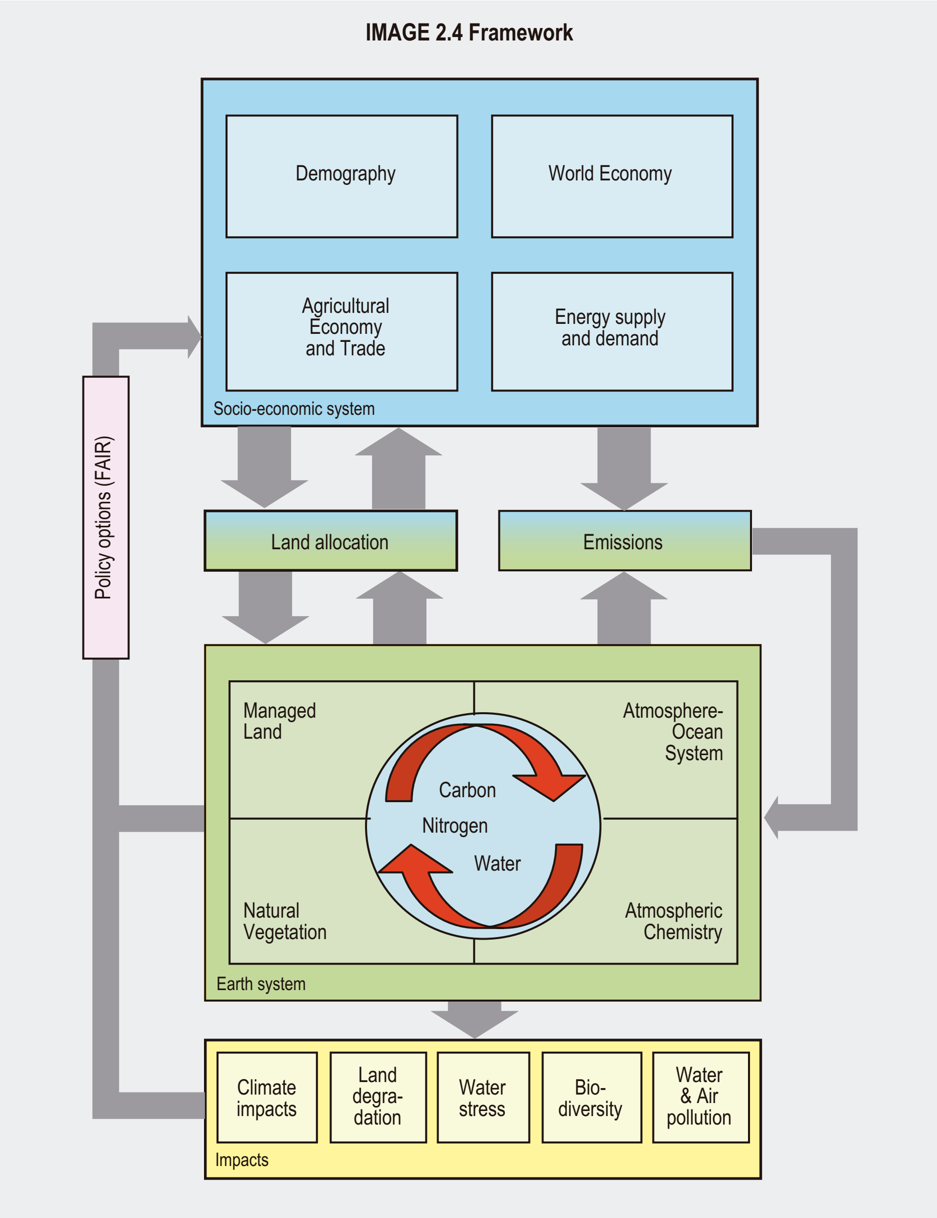


Figure 3-4 The structure of the IMAGE-2 model.

IMAGE 2 is global in application but all land-related calculations – including the terrestrial C cycle – are performed on a terrestrial 0.5^0 longitude by 0.5^0 latitude grid (while the socioeconomic aspects are performed for 18 regions). Each grid cell is characterized by its climate (i.e. temperature, precipitation, and resulting soil moisture and cloudiness), soil, topography, and land cover (natural or anthropogenic). Referring to the latter, a grid cell is assumed to consist of one out of 14 natural biomes or 6 anthropogenic land-use classes. The distribution of 14 natural biomes (7 forest, 7 non-forest) is computed with the BIOME model (Leemans & van den Born, 1994) on the basis of climate, soil, and atmospheric CO_2 concentration. When climate changes, vegetation patterns may shift. Land-cover specific time lags in these shifts are considered to explicitly mimic different migration and establishment capabilities of species due to limiting migration capabilities of species (Van Minnen *et al.*, 2000; see section 3.4.4). For example, it is assumed that the conversion from tundra into boreal forest occurs more rapidly than the conversion from one forest type to another. Anthropogenic land-cover types include agriculture (arable land and grassland), marginal grassland, and carbon and biomass plantations. Carbon (chapter 6) and biomass (Hoogwijk *et al.*, 2005) plantations have been recently added as two separate land-cover categories to deal with their effects on the terrestrial C cycle. Furthermore, "Re-growth forests" are two land-use classes in IMAGE 2, representing forest re-growth after harvesting or abandoning agricultural land.

3.4.2 Basic processes in the IMAGE-2 C-cycle model

The core of the terrestrial C-cycle model presented here was implemented in the IMAGE-2 framework as early as version 2.0 (Klein Goldewijk *et al.*, 1994). The original model has been changed to include additional feedback processes (Van Minnen *et al.*, 1995), a finer time step (Alcamo *et al.*, 1998), consideration of a transient biome shifts instead of a static change (Van Minnen *et al.*, 2000), a changed parameterization (Van Minnen *et al.*, 2006, for settings in version 2.4), and additional land-cover types such as bioenergy crops and forest plantations (see chapter 6 of this thesis). The model uses concepts of various model types, presented earlier in this chapter. Compared to early terrestrial C-cycle models, IMAGE 2 is geographically explicit and process-based, including numerous interactions and feedbacks. Compared to more complex models, IMAGE 2 reflects implementation of various simplifications with respect to processes, scales, etc., similar to other Integrated Assessment (IA) Models.

The major processes determining the terrestrial C cycle in IMAGE 2 are Net Primary Productivity (NPP, Equation 1) and soil respiration (Equation 2) (Figure 3-5), comparable with other biogeochemistry models of the 1990s. The NPP in a grid cell is calculated for every month and aggregated to an annual value. The plant responses in different seasons can be simulated using the monthly time step. This temporal resolution is also consistent with the downscaling of monthly climate-change patterns in the atmosphere–ocean system. The NPP in any grid cells "g" at a specific time "t" ($NPP_{g,t}$ t C $km^{-2}.yr^{-1}$) is a function of land cover (and its underlying initial NPPI value), history (i.e. the development of a land cover), climate, atmospheric CO_2 concentration, and soil properties (i.e. moisture and soil type). All these dependencies are described in this section.

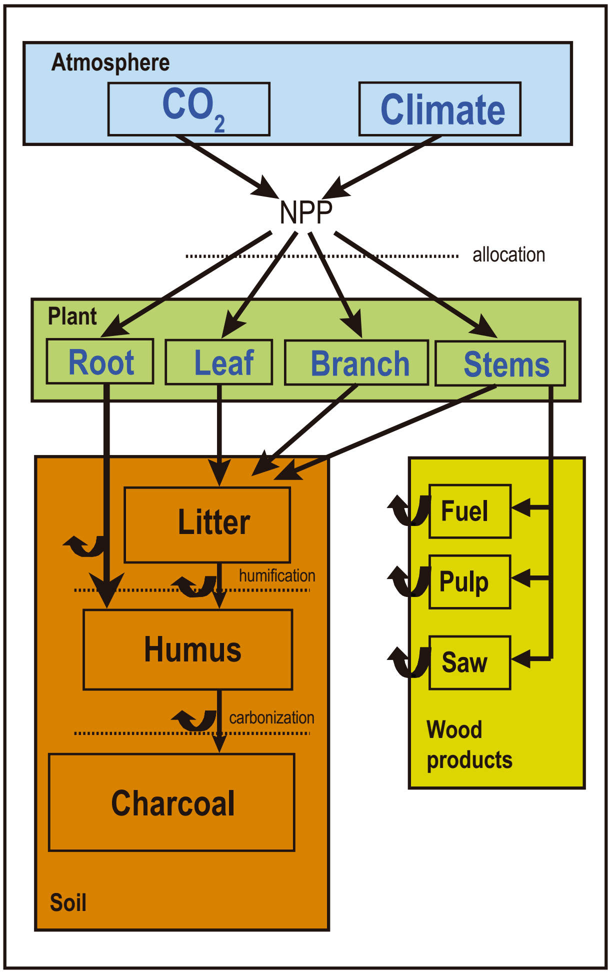


Figure 3-5 IMAGE 2 terrestrial C-cycle model showing different C pools and linkages. Fractions and fluxes are land-cover type-specific. NPP= Net Primary Production.

Equation 1

$$NPP_g(t) = NPPI_{l_g} \bullet y_{g,t} \bullet \sum_{m=1}^{12} \left(\left[1 + \beta_{g,m}(t) \cdot \ln \left(\frac{[CO_2](t)}{[CO_2](1970)} \right) \right] \cdot \sigma_{g,m}(t) \right)$$

where:

NPP	net primary production (Mg C/km^2)
$NPPI_{l,g}$	initial NPP of a biome in 1970 (Mg C/km^2) (Table 3-3)
$y_{g,t}$	factor for recovering a grid cell after harvest or for the period in which a biome in a grid converts from one type to another (-) (Equation 9)
$[CO_2]$	CO_2 concentration (ppmv);
$\beta_{g,m}(t)$	CO_2 fertilization factor
$\sigma_{g,m}(t)$	multiplier for temperature effect and water availability on plant growth (-);.
t	time (1970 – 2100);
g,	grid-cell index (1 – 66,663);
m	month index (1 – 12);
l	land-cover/biome index (1 – 20);
b_l and r_l	growth parameters for land-cover type l (-);

$NPPI_{l,g}$ is the initial mean NPP of land-cover type or biome “l”, assuming a steady-state situation (Table 3-3). This implies a situation with limited environmental stress and a global C cycle in equilibrium (i.e. C uptake equals C release). The second term of Equation 1 ($y_{g,t}$) is a factor assessing the increase of NPP (and thus the overall C dynamics) during a transient phase. The transient phase can be the result of an anthropogenic disturbance (e.g. wood harvest) after which the natural land cover recovers, or of a natural conversion as a result of climate change (sections 3.4.3 and 3.4.4, respectively). The third and fourth terms of Equation 1 represent adjustments of the NPPI value in a grid cell “g” for climatic, atmospheric CO_2 and local conditions. The third term is the so-called CO_2 fertilization effect, which is the direct effect of changes in atmospheric CO_2 on NPP. The fourth term (i.e. $\sigma_{g,m}(t)$) is the effect of changes in temperature and moisture availability. These feedbacks will be assessed in detail in the next section.

The C taken up as a result of NPP is divided in IMAGE 2 into four different living biomass compartments: leaves, branches, stems, and roots (Figure 3-5). The pools are characterized by predefined biome-specific allocation fractions and specific live times (Table 3-3). From the living biomass compartments, the carbon is transferred to either the soil litter pool (in case of leaves, branches, and stems) or the soil humus pool (for decaying roots), where it (slowly) decomposes and returns as CO_2 to the atmosphere. Alternatively, the living biomass from forests can become harvested and stored as pulpwood and particles (with a turnover rate of 10 years), veneer, and saw logs (with turnover rates of 100 years).

Table 3-3 Parameter setting of the IMAGE-2 terrestrial C-cycle model, versions 2.3 (used in chapter 4 & 6) and 2.4 (chapter 5)

	Agricultural land-cover type & natural land cover/biomes	NPPI[4] (g.m^{-2}.yr^{-1})	Allocation fraction (-)				Lifetimes (year)							Humification fraction
			Leaves	Branches	Stems	Roots	Leaves	Branches	Stems	Roots	Litter	Humus	Charcoal	
1	Agricultural land	400 (350)	0.8	0	0	0.2	1	n.a.	n.a.	1	1	*	500	0.3 (0.45)
2	Marginal grasslands	400 (350)	0.6	0	0	0.4	1	n.a.	n.a.	1	1	*	500	0.3 (0.4)
3a	Sugarcane (bioenergy)	1700	0.5	0.3	0	0.2	1	1	n.a	1	1	*	500	0.3 (0.4)
3b	Maize (bioenergy)	450	0.7	0.1	0	0.2	1	1	n.a	1	1	*	500	0.3 (0.4)
3c	Wood (bioenergy)	1100	0.3	0.2	0.3	0.2	1	1	1	1	1	*	500	0.3 (0.4)
4/5/6	Re-growth of forests from abandoned agriculture, forestry & C plantations		Values of underlying natural vegetation type used											
7	Ice	0	0	0	0	0	0	0	0	0	0	0	0	0
8	Tundra	100	0.5	0.1	0.1	0.3	1	10	50	3	2	50	500	0.5
9	Wooded tundra	300	0.3	0.2	0.3	0.2	2	10	50	10	3	50	500	0.5
10	Boreal forest	500 (350)	0.3	0.2	0.3	0.2	2	10	50	10	3	50	500	0.6
11	Cool conifer forest	550	0.3	0.2	0.3	0.2	3	10	50	10	3	40	500	0.5 (0.55)
12	Temp. mixed forest	600 (650)	0.3	0.2	0.3	0.2	2	10	50	10	2	40	500	0.5 (0.55)
13	Temp. deciduous forest	650 (700)	0.3	0.2	0.3	0.2	1	10	50	10	2	40	500	0.4 (0.5)
14	Warm mixed forest	650 (700)	0.3	0.2	0.3	0.2	1	10	50	10	2	40	500	0.4 (0.5)
15	Steppe	450 (400)	0.6	0	0	0.4	1	10	50	2	1	30	500	0.4 (0.45)
16	Hot desert	50	0.6	0	0	0.4	1	10	50	2	1	50	500	0.4
17	Scrubland	400	0.3	0.2	0.2	0.3	1	10	30	5	2	30	500	0.4 (0.45)
18	Savanna	500	0.3	0.2	0.2	0.3	1	10	30	5	2	20	500	0.4 (0.45)
19	Tropical woodland	900 (950)	0.3	0.2	0.3	0.2	1	10	30	10	2	20	500	0.4 (0.5)
20	Tropical forests	1200 (1250)	0.3	0.2	0.3	0.2	1	10	30	10	2	20	500	0.4 (0.5)

---

[4] Normal values represent setting for IMAGE 2.3; values for version 2.4 are shown in brackets.

Soil respiration $SD_{g,t}$ (Equation 2) is the C flux from the ecosystems into the atmosphere resulting from the decomposition of the three soil carbon pools. Soil respiration is calculated in IMAGE 2 on a monthly base as a function of the biomass of the different pools, their lifetimes, humification and carbonization fractions, air temperature, and soil moisture (Equation 2). During the decomposition of litter and dead roots, one part is transformed into soil humus using the humification factor (HF in Table 3-3), while the remainder is lost as CO_2 to the atmosphere. The humus pool increases as a result of decomposition of litter and turnover of roots, while a fraction is lost due to transformation into inert soil C (=charcoal) using the carbonization fraction (0.07% for all land-cover types). Charcoal is a major C pool in many biomes. Its respiration flux into the atmosphere could therefore be significant, despite its long lifetime of 500 years.

Equation 2

$$SD_g(t) = (1 - HFact_l\ ) \bullet (\frac{B_{rt,g}}{\tau_{rt}} + \frac{B_{lt,g}}{\tau_{lt}}) + (1 - CFact_l) \bullet \alpha_{sd,g,t} \bullet (\frac{B_{hm,g}}{\tau_{hm}}) + \alpha_{sd,g,t} \bullet (\frac{B_{CC,g}}{\tau_{CC}})$$

where:

$SD_{g,t}$	C release at time step t due to soil decomposition of grid cell g in year t (t C ha^{-1} yr^{1})
$B_{rt,gt}$	root biomass in grid cell g at time t (t C ha^{-1})
$Bl_{t,g}$	litter biomass in grid cell g at time t (t C ha^{-1})
$B_{hm,g}$	humus biomass in grid cell g at time t (t C ha^{-1})
$B_{cc,g}$	stable charcoal biomass in grid cell g at time t (t C ha^{-1})
τ	lifetime of roots “rt”, litter “lt”, humus “hm” and charcoal “cc” (year)
$HFact_l$	Humification Fraction (-)
$CFact_l$	Carbonization Fraction (-)
$\alpha_{sd',g,t}$	correction factor for air temperature and soil moisture availability in grid cell g in year t (-) (see next section)

In IMAGE 2, Net Ecosystem Productivity (NEP) represents the net terrestrial C flux between the ecosystems and atmosphere for each grid cell in year “t”. NEP equals NPP minus the soil respiration flux (Equation 3). A positive NEP value indicates a C sink in the terrestrial ecosystems, while a negative value indicates C emissions into the atmosphere. The NEP fluxes over all grid cells specify the global residual sink or natural terrestrial C budget.

Equation 3 $$NEP_{g,t} = NPP_{g,t} - SD_{g,t}$$

The IMAGE-2 terrestrial C-cycle model includes various feedback processes that modify the NPP and soil decomposition, and thus the NEP flux in a grid cell. These feedback processes account for changes in climate, atmospheric CO_2 concentration and land cover. The individual feedbacks can either increase NEP (or decreased CO_2 concentration, negative feedback) or decrease it (positive feedback). The net result of all feedbacks depends on the combination and strength of the individual feedback processes. The section below describes the implementation of the CO$_2$ fertilization, along with the temperature and moisture feedback for NPP and soil respiration. The algorithm used in IMAGE 2 for these feedbacks is derived from terrestrial ecosystem models, which, in turn, have often scaled up information (using the summation concept) from field experiments or local biogeochemical models. The implementation demonstrating how different land-cover conversions affect the terrestrial C cycle is described in the subsequent sections 3.4.3 and 3.4.4.

Feedback processes: CO$_2$ fertilization

Increasing atmospheric CO$_2$ levels enhance plant growth (see chapter 2 of this thesis for physiological details). Two mechanisms can be distinguished in this CO$_2$ feedback, both implemented in the IMAGE-2 terrestrial C-cycle model. First, increasing CO$_2$ levels enhances the photosynthesis of plants, which is the so-called CO$_2$ fertilization effect. Second, atmospheric CO$_2$ affects the C cycle through its effect on the water consumption of plants. Stomata can be partially closed under increasing CO$_2$ levels, since the C uptake can remain constant while transpiration rates are reduced. Due to the lowered water loss, plant species can grow under more water-limited conditions and as such extend their distribution into dryer areas. This is the so-called water-use efficiency (WUE). An increased WUE is found for various plant types and can result in the expansion of plant species into drier areas (Koch & Mooney, 1996).WUE is defined as the biomass production per unit water “consumed” by the plants (Mooney *et al.*, 1991; Mooney & Koch, 1994).

The CO$_2$-fertilization effect is implemented in the IMAGE-2 C-cycle model by using the β fertilization factor. The ß factor is currently under discussion in the literature (e.g. Alexandrov *et al.*, 2003; Friedlingstein *et al.*, 2006; Denman *et al.*, 2007). Because of the controversial view on strength of the ß factor, it has also been incorporated in an uncertainty analysis of the IMAGE-2 terrestrial C-cycle model (see chapter 4). We first defined an initial ß-factor (ß$_{ini}$), which quantifies the growth enhancement for doubling the atmospheric CO$_2$ concentration under optimal conditions. In IMAGE 2 the *ß*$_{ini}$ factor is constant over time and geographical space. Up to the 2.3 version of the model (as employed in chapters 4 & 6 of this thesis), the ß$_{ini}$ was set at 0.7, whereas it was reduced to 0.35 in IMAGE 2.4 (as in the analysis presented in chapter 5). Second, the actual ß factor is determined using – in a multiplicative way – environmental and local conditions (Equation 4). Because of this correction, the actual ß factor in the start year is in most grid cells already (much) lower than the initial value. Furthermore, the actual ß factor varies in time because of the changing environmental conditions.

Equation 4 $$\beta_{g,m}(t) = \beta_{ini} \cdot MIN\Big(f_1(T_{g,m}(t), SM_{g,m}(t)) \cdot f_2(l_g, N_g, A_g), 1.0\Big)$$

where:

β$_{g,m}$(t)	actual CO$_2$ferilization (or ß) factor in grid “g” in month “m” (-)
β$_{in}$	initial CO$_2$ fertilization factor (-)

f_1	correction function for temperature and soil water status on CO_2 fertilization (-)
f_2	correction factor for species characteristics (l), nutrient availability (N) and altitude (A) on CO_2 fertilization (-)
g	grid-cell index (1 – 66,663); m = month index (1 – 12); l = land-cover/biome index (1 – 19)

The environmental factors considered here that determine $\beta_{g,m}(t)$ in grid cells are temperature, soil-water availability, nutrient availability, species characteristics, and altitude (Figure 3-6). The effect of air temperatures on $\beta_{g,m}(t)$ has been included in the IMAGE-2 terrestrial C-cycle model by assuming no CO_2 fertilization below a certain minimum temperature, followed by a linear increase up to a maximum value (Figure 3-6a). Both the minimum and maximum temperatures are biome-specific (Table 3-4). Soil moisture availability influences $\beta_{g,m}(t)$ in a such a way that it becomes more pronounced under xeric conditions. A linear relationship was assumed (Figure 3-6b), starting with a factor of 2.5 for dry regions, and decreasing towards 1 for no moisture-limited conditions. Third, a relationship between the $\beta_{g,m}(t)$ and the soil nutrient availability is considered (Figure 3-6c). Under poor conditions, the CO_2 fertilization effect can be limited (Bazzaz & Fajer, 1992, Melillo *et al.*, 1996; Alexandrov *et al.*, 2003; Körner *et al.*, 2005), although the nutrient efficiency ratio of plants can increase at enhanced CO_2 levels (e.g. because of an improved nutrient use in enzyme processes; Bowes, 1993). In IMAGE 2 this feedback is implemented by using grid-cell specific soil fertility derived from the FAO Soil Map of the World (see Leemans & van den Born, 1994). The multiplication factor equals zero if no soil is available (e.g. ice), and ranges from 0.7 for soils with a low fertility to 1 for fertile soils. Fourth, the CO_2-fertilization effect depends on the species composition in a biome (Figure 3-6d). This is implemented by defining for each biome and underlying plant function types (PFT) the ratio of so-called C_3 (e.g. wheat, most temperate grass species, and many tree species) versus C_4 species (e.g. maize, tropical grass species), and of grasses versus tree species (Table 3-4). The growth response to increased CO_2 levels is larger in C_3 than in C_4 species (Bazzaz *et al.*, 1989; Goudriaan & Zadoks, 1995, An *et al.*, 2005) and in tree species versus herbaceous species (Bazzaz, 1990; Körner, 1993; Bazzaz, 1998). I used a correction factor of 1 for C_3 species and 0.3 for C_4 species. Finally, altitude affects $\beta_{g,m}(t)$ (Figure 3-6e), assuming no effects below the 600 m above sea level and a linear relationship up to 4600 m (Körner & Diemer, 1987). The basis is that biomes at high elevations are more C-limited than species at low altitudes, because of the differences in air pressure. As such, plants at high latitudes will response more to a doubling of the atmospheric CO_2. The assumed relationship implies that at 4600 m above sea level biomes respond three times more than at 600 m.

Feedback processes: Effect of climate change on Water Use Efficiency

Changes in WUE are implemented in IMAGE 2 by using a relationship between the CO_2 concentration in the atmosphere and the moisture threshold below a plant functional type (PFT) can not grow in an area. These possible changes in PFT and,

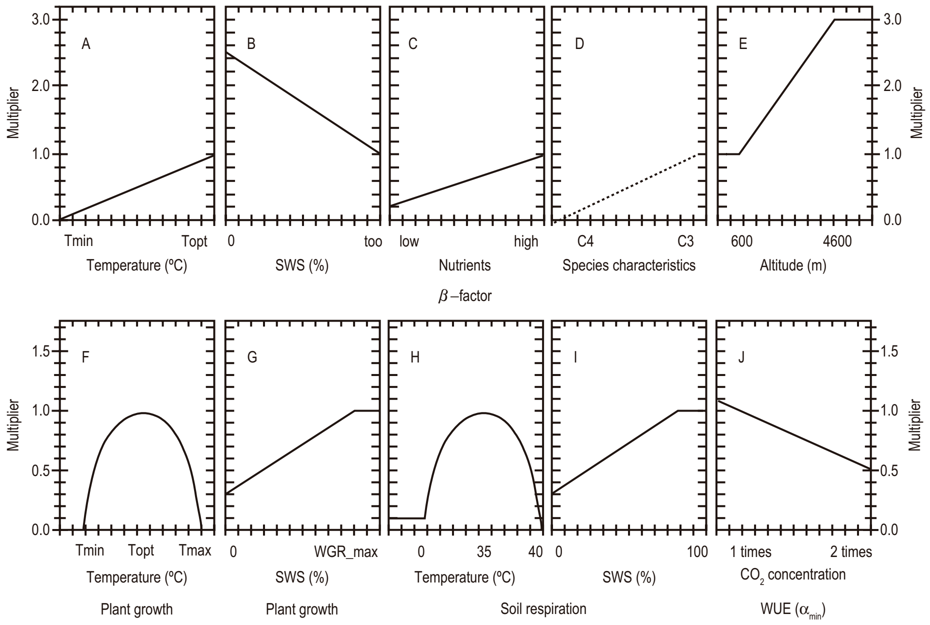


Figure 3-6 **The influence of environmental conditions on C-cycle processes in IMAGE 2. The top diagrams represent the adjustments of the CO_2 fertilization factor $\beta_{g,m}(t)$, while the lower diagrams depict the effect on plant growth, soil decomposition, and water-use efficiency.**

consequently, the biome are taken up by the IMAGE-2 C-cycle model in order to estimate the consequences for the terrestrial C cycle (see section 3.4.4).

Feedback processes: Effect of temperature and moisture on NPP

Temperature and moisture availability are two main drivers of both plant photosynthesis and plant respiration (see also chapter 2). A multiplicative approach is implemented in the IMAGE-2 terrestrial C-cycle model to simulate the net effect on NPP of changes in both drivers, using a monthly time step (upper part of Equation 5). The net effect has been normalized to the biome-specific average value (lower part of Equation 5) to have the NPP averaged over all grid cells covered by biome type "l" equal NPPI (Equation 1) in the initial year (i.e. 1970).

Equation 5 $$\sigma_{g,m}(t)=\frac{f_1(T_{g,m}(t),l_g)\cdot f_2(SM_{g,m}(t))}{AF_{l_g}}$$

$$AF_{l_g}=\frac{\sum_{i\wedge i\in l}\left(\sum_{m=1}^{12}\left(f_3(T_{i,m}(1970),l_i)\bullet f_4(SM_{i,m}(1970))\right)\right)\bullet area_i}{\sum_{i\wedge i\in l}area_i}$$

where:

$\sigma_{g,m,}(t)$	multiplier for temperature effect and water availability on plant growth (-)
f_3	multiplier for direct temperature effect on plant growth (-)
f_4	multiplier for water availability effect on plant growth (-)
T	monthly temperature (°C)
SM	monthly soil-water status (%)
AF	normalization factor to 1970 average (-)
area	grid-cell area (km^2)
t	time (1970 – 2100)
g	grid-cell index (1 – 66663)
m	month index (1 – 12)
l	land-cover index (1 – 20)
I	index of all grid cells in one biome type in 1970 (subset of g)

Table 3-4 Biome-specific parameters for environmental conditions on NPP, as implemented in the IMAGE-2 C-cycle model

		Temperature (°C)			Species correction factor[1]	SMS_{max} (%)	VAR[1]
Nr.	Land-cover class/biome	min	opt	max			-
1	Agricultural land	0	25	45	0.85	50	-
2	Extensive grassland	0	25	45	0.85	50	-
3	Bioenergy crops	0	19	35	0.85	50	-
4/5/6	Re-growth forests from abandoned agriculture, forestry & C plantations	Values of underlying natural vegetation type used					
7	Ice	-100	0	5	0	50	-
8	Tundra	-5	15	45	0.95	70	1.06
9	Wooded tundra	-4	16	45	0.95	70	1.05
10	Boreal forest	-3	17	45	0.95	70	1.04
11	Cool conifer forest	-2	18	45	0.95	70	1.02
12	Temp. mixed forest	-1	19	45	0.95	70	1.0
13	Temp. deciduous forest	-1	20	45	0.95	70	0.97
14	Warm mixed forest	0	24	45	0.97	70	0.83
15	Steppe	1	27	50	0.70	50	0.83
16	Hot desert	1	31	50	0.65	10	0.70
17	Scrubland	0	31	50	0.90	50	0.69
18	Savanna	1	30	50	0.86	60	0.73
19	Tropical forest	1	27	50	0.93	70	0.83
20	Tropical forest	2	28	50	0.97	80	0.83

[1] Species correction factor, based on the ratio of non-grass:tropical grass:temperate grass; and maximum of soil moisture status (SMS), beyond which NPP is not limited by soil moisture. The variable VAR is needed in Equation 8

Temperature affects NPP directly through its effect on photosynthesis and plant respiration (Larcher, 2003). Photosynthesis starts at a minimum temperature, increases up to an optimum temperature and then decreases. Plant respiration increases exponentially. These two responses are combined in the IMAGE-2 C-cycle model by using a single reversed parabolic response function (Figure 3-6f, Equation 6), derived from the TEM model (McGuire *et al.*, 1997) and based on Larcher (2003). Above T_{max}, the plant respiration is higher than photosynthesis, resulting in an NPP of zero. Below T_{min} both photosynthesis and respiration are low, resulting in an NPP rate close to zero. T_{min}, T_{opt} and T_{max} are all biome specific (Table 3-4).

Equation 6 $$f_1(T_{g,m}(t), l_g) = \frac{(T - T_{\min})(T - T_{\max})}{[(T - T_{\min})(T - T_{\max})] - (T - T_{opt})^2}$$

where:

T	the actual monthly average temperature in year t (°C)
T_{min}	the land-cover specific minimum temperature (°C)
T_{max}	the land-cover specific maximum temperature (°C)
T_{opt}	the land-cover specific optimum temperature (°C)
t	time (1970 – 2100)
g	grid-cell index (1 – 66,663)
m	month index (1 – 12)
l	land-cover/biome index (1 – 20)

The effect of changing soil moisture on NPP (function f_2 in Equation 5) is implemented in the IMAGE-2 C-cycle model by using a linear function with the monthly soil water status (SWS, Figure 3-6g). This function increases from 0.3 up to 1, at which no growth limitation occurs. The lower boundary is based on the assumption that moisture availability is rarely zero for an entire month. The values of SWS at which no growth limitation occurs (SMS_{max}) are biome-specific (Table 3-4).

Feedback processes: Effect of temperature and moisture on soil respiration

Decomposition of soil organic carbon is strongly related to the availability of moisture and soil temperature (Kätterer *et al.*, 1998; Davidson & Janssens, 2006). The net effect of both factors is implemented in the IMAGE-2 C-cycle model by using a multiplicative approach (Equation 7).

Equation 7 $$\alpha_{sd,g,t} = s_1(T_{g,m}(t)) * s_2(SWS_{,m,g}(t))$$

where:

$\alpha_{g,m,}(t)$	multiplier for temperature effect and water availability on soil respiration (-)
s_1	multiplier for direct temperature effect (-)
s_2	multiplier for water availability effect (-)
T	monthly temperature (°C)

SWS	monthly soil-water status (%)
T	time (1970 – 2100)
g	grid-cell index (1 – 66,663)
m	month index (1 – 12)
l	land-cover/biome index (1 – 19)
I	index of all grid cells in one land-cover type in 1970 (subset of g)

The temperature dependency of soil decomposition is implemented in IMAGE 2 by using a parabolic relationship similar the temperature effect on plant growth (Figure 3-6g, Equation 8). Below T_{min} and above T_{max} the decomposition rates are low, and reach a maximum at T_{opt}. The function is an adapted version of the function in the CENTURY model (Parton *et al.*, 1994). The variable VAR is introduced in IMAGE 2 to enable a broader application of this function for different biomes (Equation 8, Table 3-4). The variation of VAR among biomes is particularly related to the wood content of the soil carbon pools, distinguishing between tundra, grassland, and scrubland types on one site, and forests on the other. The strength of the response of soil decomposition to climatic changes is still under scientific discussion (see reviews by Knorr *et al.*, 2005; Davidson & Janssens, 2006). This is reflected, for example, in the fact that many models assume a doubling of the specific respiration rate for every 10 °C warming (i.e. $Q_{10} = 2$) (see Friedlingstein *et al.*, 2006 for the C_4MIP model comparison). Such a Q_{10} relationship between soil decomposition and temperature has, however, not been noted at the whole ecosystem level for decadal time scales, either in forest soils (Giardina and Ryan, 2000, Melillo et al., 2002; Dunn et al., 2005), or grasslands (Luo et al., 2001). In order to evaluate the consequences of such a Q_{10}-relationship in IMAGE 2, I included soil decomposition as one of the processes in the uncertainty analysis of the C-cycle model (chapter 4 of this thesis).

Equation 8

$$s_1(T_{g,m}(t), l_g) = [\frac{T_{\max} - T}{T_{\max} - T_{opt}}]^{0.2} * \exp(0.076 \bullet (1 - [\frac{T_{\max} - T}{T_{\max} - T_{opt}}]^{VAR}))$$

where:

T	the actual monthly average temperature in year t (°C)
T_{min}	the land-cover specific minimum temperature (°C)
T_{max}	the land-cover specific maximum temperature (°C)
T_{opt}	the land-cover specific optimum temperature (°C)
VAR	parameter (land-cover specific, -)
t	time (1970 – 2100);
g	grid-cell index (1 – 66,663);
m	month index (1 – 12);
l	land-cover/biome index (1 – 19);

In IMAGE 2 soil decomposition is linearly related to the soil-water status in each grid cell (Figure 3-6h). The assumption made is that even under dry circumstances, some decomposition occurs, while the maximum effect is set for attainability at 70% saturation. The effect is assumed to be biome-independent.

3.4.3 Anthropogenic induced land-cover changes and their effect on the C cycle

One of the most important parts of the IMAGE-2 model is the geographically explicit land-use and land-cover modeling, where different demands for food, fodder, timber, bioenergy, and carbon sequestration (i.e. plantations) are considered. In this respect, IMAGE 2 explicitly distinguishes four anthropogenic land-cover conversions:

- natural vegetation to agricultural land (either cropland including energy, or crops or pasture)
- forests to “re-growth forest” as a result of wood (i.e. timber or fuel) harvest
- agricultural land to natural land-cover types
- agricultural land or forests to forest plantations to sequester carbon.

Because of their considerable effects on the terrestrial C pools and fluxes, I describe these conversions as implemented in IMAGE 2 in more detail,

From natural biomes to agricultural land

In IMAGE 2 conversions from natural biomes into agricultural land (both cropland and pasture) result in an instantaneous change of the C characteristics. The NPP values shift from the natural biome towards values typical for agriculture and pasture. Different assumptions are made for tropical and non-tropical biomes with respect to the release of the above-ground C. For the biomes “warm mixed forest”, “scrubland”, “savanna”, and “tropical woodland and forests”, land-use changes are assumed to result in a major loss of the above-ground C pool into the atmosphere, while a small part will enter (5%) the inert soil C (charcoal). The root C pool enters the humus soil compartment entirely. This approach mimics biomass burning, which is common practice in many tropical areas (Houghton, 2003; Cramer *et al.*, 2004). For the other biome types, it is assumed that land-use changes will result in a flux of non-woody C compartments into the litter and humus pools, while the woody biomass is used to satisfy the regional and global wood demand.

From version 2.3 onward, IMAGE 2 has explicitly considered energy crops as a separate biome type. Three energy crops are distinguished: sugarcane, maize, and “wood” (i.e. fast-growing tree species like poplar and willow in short rotation cycles). The explicit consideration of energy crops enables modeling:

(i) the competition between agricultural land for growing either energy, food, or feed crops and

(ii) the consequences for the C cycle of using abandoned agricultural land for either energy crops or carbon plantations, or letting it recover to a (more or less) natural state (Van Vuuren *et al.*, 2007). The parameters for energy crops in the IMAGE-2 C-cycle model are set to focus on growing crops that capture carbon (and thus energy) instead of maximizing the size of the "edible" parts. This is also shown in (Table 3-3), where the NPPI values of energy crops are higher than the average values for agricultural land. These high NPPI values were obtained by matching the energy crop results of the C-cycle model as closely as possible to the agricultural model (in terms of C). The temperature response curve on NPP has been adapted for energy crops (Table 3-4) to match the energy crop yields in different (latitudinal) regions.

Wood harvest

IMAGE 2 distinguishes between timber and fuel-wood harvests because of differing consequences for the C budget. The C stored in timber is released only slowly into the atmosphere (pulpwood and particles have a turnover rate of 10 years, and veneer and saw logs have turnover rates of 100 years), while fuel wood – being burned – leads to instantaneous C release.

In IMAGE 2 wood harvest results in a decline of the C pools, followed by a period of re-growth. The approach is similar to the one used for the afforestation of abandoned agricultural land (described below). During the re-growth period, the land cover in a grid cell will be classified as "re-growth forest" if the forest exploitation results in more than 50% reduction of the woody biomass. Re-growth forests cannot be used again until NPP has recovered to 99% of the NPP (up to version 2.3) or until the stem biomass is back to 80% of a land-cover-specific equilibrium value (version 2.4). These criteria have been implemented in order to mimic the forestry rotation period. The latter criterion has been recently introduced, because the former led to a premature re-use of an area. Even if the NPP returned to normal values, time is needed to get a stem biomass that is suitable for particularly timber.

Abandoned agricultural land

The third type of land-cover change that has been included in IMAGE 2 is the conversion of agricultural land into a natural biome. Such a "reverse" land-use change can occur if agricultural land is abandoned because of: (i) a regional surplus of agricultural land (e.g. due to decreasing population, increasing productivity, and increasing trade) or (ii) a too low productivity (e.g. climate change may result in a decreased suitability). The land-cover model of IMAGE 2 deals with reverse land-cover changes by converting the actual land-cover in a grid cell (i.e. agriculture) into its potential natural biome type. If the potential biome type belongs to one of the seven forest types, the land cover will be categorized first as "re-growth forest".

The consequences for the C budget within IMAGE 2 are that root and litter C pools are shifted to the humus compartment and that the NPP slowly recovers, following a logistic type of curve towards the natural biome-specific "equilibrium" value (Equation 9, Dewar & Cannell, 1992). The variable "recov" depicts the time period needed by natural biomes to recover after abandonment of agriculture. The values are set by averaging and enlarging information from forest yield models and yield tables.

Equation 9 $$y_{g,t} = \frac{1}{1+99\exp[-9.2 \bullet (t_o - t)/_{recov}]}$$

where:

$y_{g,t}$	the fractional increase in NPP in grid cell g at year t (Equation 1, -)
recov	the land-cover/biome-specific recovery period (yr, Table 3-5)
t_0	the starting year of the conversion
t	time (1970 – 2100)

Carbon plantations

Carbon plantations have been introduced recently in IMAGE 2 as a new land-cover class for assessing land-use related activities as options for achieving stabilization of the atmospheric CO_2 concentration – the ultimate objective of Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC, 1993). These activities are often referred to as “land-use change and forestry (LUCF)” or “carbon sinks” activities. The presumption underpinning the sinks is that avoidance of a build-up of carbon (or other greenhouse gases) in the atmosphere also leads to avoidance of climate change (impacts), regardless of the origin of the carbon.

The different steps of the implementation of these LUCF activities in IMAGE 2 and the consequences for the global and regional C cycle are described in detail in chapter 6 of this thesis. One key assumption is that only the net C-sequestration potential is determined by quantifying the additional C sequestration by C plantations. This is compared to the natural land cover that would otherwise grow at the same location plus the C losses associated with the conversion from natural land cover to a plantation. Hence, all C fluxes and pools in vegetation and soils are considered, including the C losses due to the establishment of the plantations. This net C balance and full accounting are two main requirements accounting for C sinks under the UNFCCC and the underlying Kyoto Protocol. The C sequestration potential of the plantations was defined by averaging and enlarging information from forest yield models and yield tables, as presented in the literature (see chapter 6 of this thesis).

3.4.4 Natural land-cover conversions and the effect on the C cycle

Like land-use changes, natural conversion from one biome to another also alters the C dynamics. Therefore such conversions are important for the IMAGE-2 C-cycle model as well.

Climate is one of the main drivers of large-scale biome distribution (Woodward, 1987, Prentice *et al.*, 1991). Therefore changes in climatic conditions result in changes in species composition within ecosystems and, in the end, in natural biome changes.

The distribution of biomes is simulated in IMAGE 2 by using an adapted version of the BIOME model (Prentice *et al.*, 1992; Leemans & van den Born, 1994), one of the most frequently used biogeographical models. BIOME represents biomes as collections of plant functional types (PFTs) allowing a large-scale representation of plant species aggregated according to physiological characteristics (e.g. needle- or broad-leafed trees, grasses, and desert plants). PFTs respond individually to changes in temperature, growing season and water availability, and have different competition capabilities. The BIOME model assumes that biomes are in equilibrium with the prevailing climate. This assumption is valid for millennium time scales, but less appropriate for simulating the effects of rapid climate change on decadal and centennial time scales (e.g. Smith *et al.*, 1993; Dyer, 1995, Sitch *et al.*, 2003).

Because the IMAGE-2 model concerns the decadal and centennial time scales, the model includes a lagged transition algorithm, combining the "migration of " and "competition between" plant species (Van Minnen *et al.*, 1995; Van Minnen *et al.*, 2000). The transition algorithm in IMAGE 2 introduces spatial dependency and transient land-cover transitions based on expanding information on mainly gap models. The algorithm consists of two stages, *dispersion* and *biome development*. The latter combines the stages "establishment" and "maturing" used by others (e.g. Solomon *et al.*, 1981; Huntley & Webb, 1989; Neilson, 1993, see also chapter 2).

In IMAGE 2 the *dispersion* stage is based on three variables: Dispersion distance D (km), dispersion rate r (km yr^{-1}) and time t (Figure 3-7, Table 3-5). The dispersion distance D is defined as the distance around a specific grid cell in which propagules and immature plants of the PFTs in biome A of grid cell i have entered. The success of this dispersion and the new biome type's ability to mature and compete with the original biomes depend on the prevailing climatic conditions. Currently, the assumption is that the dispersion is identical in all directions, ignoring factors like landscape characteristics, prevailing wind direction, and waterways. D increases in time t with biome-specific dispersion rates until the maximum dispersion distance D_{max} has been reached (Table 3-5).

The "dispersion" algorithm of IMAGE 2 distinguishes three stages (Figure 3-7). First, during the initialization of the model (t=0), it is assumed that biome A in a grid cell i is in equilibrium with climate, so that distance D equals D_{max} (Figure 3-7a). After climate change at a certain moment (t=1,n) has triggered a change from biome B towards A in grid cell j, the distance is determined between grid cell j and i (and other grid cells covered by biome A) and compared with the dispersion distance around cell i (Figure 3-7b). If the distance is shorter than the dispersion distance, it is assumed that propagules and immature plants from cell i could, and thus have, reached j (grid cell j_1). Consequently, dispersion is not a limiting factor, and the C pools gradually convert toward the characteristics of the new biome type A (i.e. the second stage). If, however, the dispersion is limited (i.e. distance between j and i is larger than the dispersion distance D), the conversion will not start and the original biome will remain (grid cell j_2 in Figure 3-7b). The limitation disappears when grid cell j_2 eventually becomes included in the dispersion distance D of a grid cell with biome A. This can occur if D around i increases with time as a function of the dispersal rates r (Table 3-5). Alternatively, other grid cells around j_2 may first convert into A (Figure 3-7d). This is the third stage of the IMAGE-2 dispersion algorithm.

In the aforementioned second stage of the transition approach, the old biome B will gradually disappear and be replaced by A . During this period characteristics of the C balance like initial NPP, the lifetime of different C pools and allocation fractions, gradually convert towards the values of the biome A. Different possible formulations to implement this second stage in the IMAGE-2 C-cycle model, varying in complexity, have been compared (Van Minnen *et al.*,1996; Van Minnen *et al.*, 2000). The result was a simple, linear approach.(Figure 3-8). Although it is less flexible with respect to analyzing the underlying aspects of land-cover conversions (see, for example, (Smith & Shugart, 1993), the linear approach showed long-term results that were comparable to more detailed concepts. The time T needed for this third stage is conversion specific (Table 3-6). It has been defined by examining the causes of a conversion (e.g. is a decline in B mainly due to deteriorating environmental conditions or more due competitive advantages of biome A?), and the characteristics of the original and new biome types (e.g. the time needed for biome A to establish and mature). This resulted in, for example, longer conversion times if PFTs within biome A have to appear (i.e. establish and mature) than if PFTs only have to disappear. See Van Minnen *et al.* (1996, 2000) for more details.

Table 3-5 Biome-specific periods (yr) required in IMAGE 2 for recovery after abandonment of agricultural activities, and maximum dispersion distances and rates (km and km per century, respectively)

No.	Land-cover class/biome	Recovery period (yr)	Max. dispersion Distance (km)	Rate ($km.10yr^{-1}$)
7	Ice	n.a.	-	-
8	Tundra	15	500	1500
9	Wooded tundra	20	250	750
10	Boreal forest	50	125	250
11	Cool conifer forest	50	62	250
12	Temp. mixed forest	50	125	250
13	Temp. deciduous forest	40	62	150
14	Warm mixed forest	40	125	100
15	Steppe	8	500	2000
16	Hot desert	15	1000	1000
17	Scrubland	20	500	500
18	Savanna	30	250	400
19	Tropical forest	30	125	250
20	Tropical forest	30	62	100

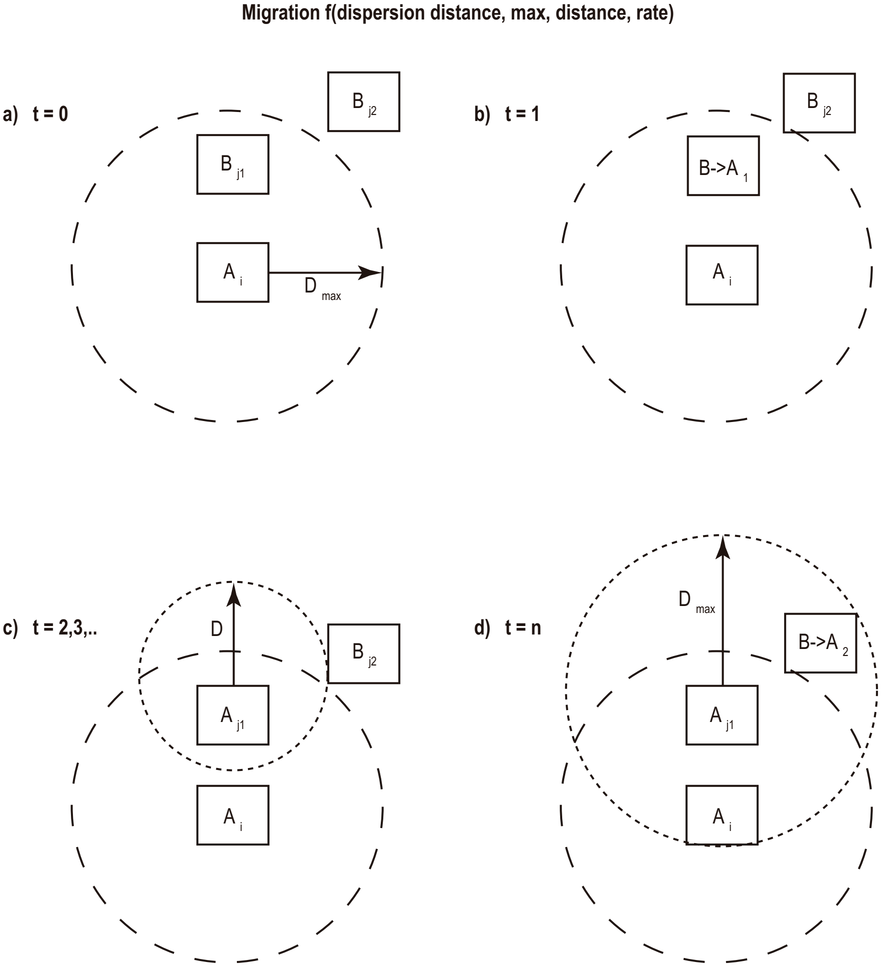


Figure 3-7 Successive stages in the migration of Plant Functional Types in IMAGE 2.

After the biome type in a grid cell has been changed, propagules start to disperse (grid cell j_1 in Figure 3-7c), again as a function of the dispersion rate r. The maximum dispersal distances, D_{max} and dispersal rates r, are biome-type specific (Table 3-5). The values are set by defining "Representative" species for each biome and evaluating the literature for characteristics like seed longevity and weight, and other factors that influence dispersal (Van Minnen *et al.*, 2000). For example, grasses grow fast and are assumed to be widely dispersed, therefore migrating rapidly over long distances. Tree species grow and disperse more slowly, and have smaller migration potentials. Note that the defined dispersal rates are at the high end of the reported literature values (Davis, 1981; Huntley & Webb, 1988; Huntley & Webb, 1989; Davis & Sugita, 1997; Huntley *et al.*, 1997). I assume that (i) historical migration rates could be lower because climate change has occurred at a much slower pace and many species have the capability to migrate faster (Pitelka, 1997), and (ii) faster dispersion is very likely if ecotones with forwarded colonies are considered instead of a mean, more continuous, population migration (the so-called "jump-dispersal" theory, Kullman,1996; Davis & Sugita, 1997).

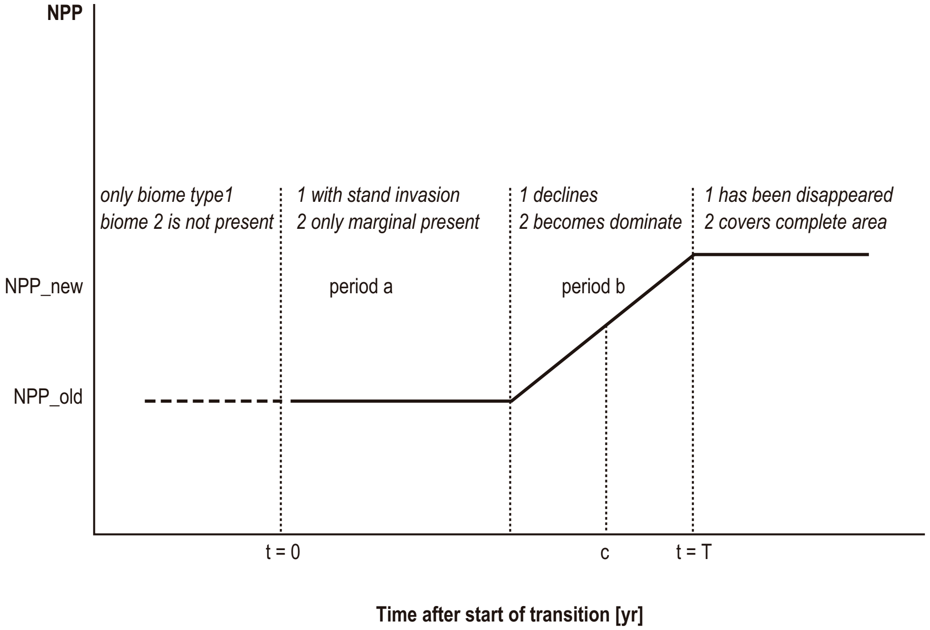


Figure 3-8 **The evolution of NPP during a biome shift (“a” is time period in which the existing biome type is able to withstand the new biome, “b” the period in which the new biome matures, and ”c” the point in time that the land cover assigned to a grid cell converts towards the new biome, and the new biome starts to disperse into new areas).**

Table 3-6 **Assumed transition periods T as used in IMAGE 2 for the conversion of natural land-cover types (years), where transitions not listed are not possible**

From	Towards biome													
biome	7	8	9	10	11	12	13	14	15	16	17	18	19	20
7 Ice	-	20							15	25				
8 Tundra	25	-	35					60	10	25	20			
9 Wooded tundra		35	-	60				60	10		25			
10 Boreal forest			60	-	70	70		70	25					
11 Cool conifer forest				60	-	80	80		25					
12 Temp. mixed forest				60	60	-	70	70	25					
13 Temp. deciduous forest					60	70	-	70	25		40	60	70	70
14 Warm mixed forest		30	35	50		50	50	-	25		40			
15 Steppe	20	10	15	60	60	65	70	70	-	10	25			
16 Hot desert	25								10	-				
17 Scrubland		25	30				50	50	25		-	35		
18 Savanna								70			25	-	35	
19 Tropical forest								80				30	-	60
20 Tropical forest								80					50	-

Note: See Van Minnen *et al.*, 1996 for the ecological background of the transition periods.

In chapter 4 of this thesis different assumptions regarding the migration potential of biomes will be compared to illustrate the spectrum of consequences for the terrestrial C cycle of considering or ignoring spatial dynamics.

3.5 Summary

The main objective of this chapter has been to describe the terrestrial C-cycle model of IMAGE 2. I motivated the model's structure and algorithms by placing the model in the broader discussion on terrestrial C-cycle models and scales.

Terrestrial C-cycle models differ with respect to the objectives and scales. Furthermore, these models have become more complex (e.g. DGVMs) and comprehensive (e.g. coupled climate-biogeochemical models), in general leading to a more accurate understanding of the terrestrial C cycle and more robust projections. Nevertheless, many terrestrial C-cycle models include several crude assumptions (for example, on ecosystem management and land use). Furthermore, we should consider whether the increasing detail – including a higher data demand and increasing computational expanses — is needed in the context of the objectives of a model? Integrated Assessment Models (IA) like IMAGE 2, for example, are developed for policy support, requiring large-scale applications, long-time series, and multiple-scenario analysis. For such models, the challenge is to find a balance between scientific rigour and policy needs.

Subsequently, I introduced the issue of scales and scaling in terrestrial C-cycle modeling. Scales are important because of the role of the terrestrial biosphere in the global C cycle, as it includes many processes that operate over a range of temporal, spatial, and organizational scales. Given the pervasive influence of scale on any conclusions reached, it is essential that assessments be explicit when referring to the geographic and temporal extent for which a study is valid. The same applies for datasets used in assessments (see also MA, 2005).

In section 3.4 I have described in detail the IMAGE-2 terrestrial C-cycle model. This model includes components that have been derived from various other C-cycle model types like gap, terrestrial ecosystem and biogeographical models. Compared to more simple, early terrestrial C-cycle models, IMAGE 2 is implemented on a geographical grid, and includes physiological and biogeographical processes. Compared to more complex models, various generalized processes and statistical relationships have been implemented in IMAGE 2 with respect to processes and scales. Ecosystem growth, for example, was implemented by using an average NPP value for each biome that becomes adapted for climatic and local conditions in each grid cell. These simplifications limit the applicability of IMAGE 2 with respect to projecting short-term and local information (e.g. the consequences of extreme droughts and fires). Furthermore, the reduced-form algorithm of various processes, and the focus on biogeochemical fluxes, limit the potential to link the IMAGE-2 C-cycle model to detailed climate models. These latter models need detailed biogeophysical information (e.g. on daily or even hourly evapotranspiration). The strength of the IMAGE-2 C-cycle model lies in the long-term perspective and integration of various biogeochemical, biogeographical, and socio-economic dimensions. Furthermore, similar to other IA models, IMAGE 2 has the advantage of estimating policy-relevant indicators such as the atmospheric CO_2 concentration (see also chapter 5 of this thesis). Finally, due to its intermediate complexity, the IMAGE-2 C-cycle model is able to run large numbers of simulations and scenarios.

Throughout this chapter various issues have been described that still remain controversial in modeling the terrestrial C cycle. Examples are the CO_2 fertilization effect (Denman *et al.*, 2007; Friedlingstein *et al.*, 2006) and the soil decomposition response to increasing temperature (Knorr *et al.*, 2005; Davidson & Janssens, 2006). With respect to the former, a major issue, for example, is whether the CO_2 fertilization effect will stabilize in the future. Regarding the soil decomposition response, most C-cycle models assume approximately a doubling of the specific decomposition rate for every 10 °C warming. Such a Q_{10} relationship was not found at the whole ecosystem level for decadal time scales in different ecosystem types. A number of these uncertainties will be taken up in subsequent chapters of this thesis.

Chapter 4

Modeling the global and regional consequences of ecosystem response to climate change through assessment of uncertainties [1]

---

[1] This chapter has been published as:

Van Minnen, J.G., B.J. Strengers, B. Eickhout, S. Brinkman, & R. Leemans (2008)
Ecological Modelling, submitted

Abstract

We performed various modeling experiments to assess the uncertainty in ecosystem processes in the response to climate change. Assessing the uncertainties is crucial for improving the understanding of the present and future role of terrestrial ecosystems in the global carbon (C) cycle. Terrestrial ecosystems currently sequester C, and thus slow the growth rate of the atmospheric CO_2 concentration. Because of the many processes involved that change over time and space and interact in a complex way, it is uncertain whether this sink will remain. We developed an experimental design in which relevant processes were evaluated systematically and the resulting changes and their consequences were assessed both globally and regionally. The experiments dealt with (combinations of) biogeochemical (i.e. temperature, moisture availability, CO_2 concentration) and biogeographical (i.e. migration ability of species) drivers and land use.

The C pools and fluxes, and the resulting CO_2 concentration have revealed considerable differences between the experiments. Responses to the process were often relevant on a typical scale. Globally, the process with the largest impact on the C cycle was CO_2 fertilization. Differences between the experiments were even larger than uncertainties in future land use. On a regional scale, CO_2 fertilization and soil respiration are the most important in tropical regions. The C cycle in high latitudes is sensitive to CO_2 fertilization and climate feedbacks. Overall, the experiments showed that C fluxes governed by terrestrial ecosystems depend considerably on the selected parameterizations and their underlying assumptions. CO_2 fertilization, in particular, can double or even triple the productivity of several ecosystems across the world. The possibility of such an increase needs to be analyzed because it is this increase that plays a strong role in determining the overall response. Furthermore, the non-linear responses and the geographical and temporal variation of responses between experiments highlight the importance of considering the ecosystem responses to various pressures simultaneously.

4. Modeling the global and regional consequences of ecosystem response to climate change through assessment of uncertainties

4.1 Introduction

The increased carbon dioxide (CO_2) concentration in the atmosphere– from about 280 parts per million (ppm) around 1880 to the current level of 380 ppm –is one of the main factors causing the current changing climate (Hegerl *et al.*, 2007). Although fossil fuel emissions are dominant in this CO_2 increase, the terrestrial biosphere also plays a substantial role (Denman *et al.*, 2007). Land-use conversions, such as deforestation, have contributed considerably to the atmospheric CO_2 increase over the past three centuries (Houghton, 2003; Van Minnen *et al.*, 2008). Current land-use changes cause emissions of 1–2 Pg C yr^{-1}, which is considerable compared to the global fossil fuels emissions of 7.3 Pg yr^{-1}. At the same time, the remaining natural biosphere – together with the ocean – sequesters about 55% of the emitted CO_2, thus slowing the atmospheric CO_2 increase. Current, and possible, future biospheric sequestration is uncertain (Denman *et al.*, 2007). This is because global terrestrial soil and vegetation C pools are determined by multiple biogeochemical and ecological processes that change rapidly over time and in space. A thorough understanding of these processes and interactions is required to project future changes in atmospheric concentrations. This understanding includes their dependency on environmental drivers (e.g. atmospheric CO_2 concentration, climate, nitrogen deposition) and land use. Furthermore, knowledge of the interactions between the processes is essential for evaluating policy options for limiting climate change, such as the cultivation of biofuel crops or establishment of C plantations.

Field and laboratory experiments (see Papale & Valentini, 2003 for overview), along with model exercises used to be performed to analyze the consequences of uncertainties in land use, climate and ecosystem response on the terrestrial C cycle. Most studies, however, did not integrate these aspects, but focused mainly on one or a few elements. For example, Cramer *et al.* (2001), Joos *et al.* (2001) and Friedlingstein *et al.* (2003) have focused on the effects of changing CO_2 concentrations and climate on the terrestrial C cycle. Sitch *et al.* (2005) evaluated the role of land-use changes; while Davidson & Janssens (2006) analyzed the consequences of different parameterizations of soil responses to climate change. Finally, Guisan & Thuiller (2005) stressed the importance of the migration ability of species in response to climate change. It is difficult to compare and synthesize the results of these studies because of differences in assumptions, models, and scales. Furthermore, the studies seldom allow for comparing the consequences of different parameterizations in the C cycle with the consequences of land use and socio-economic scenario development.

The objective of this study is to present the consequences of uncertainties in the ecosystem response to land-use and climate change for the C cycle in different regions and ecosystem types (i.e. biomes) up to 2100. Van Minnen *et al.* (1995) and Leemans *et al.* (2002) have assessed the global consequences in general terms. We have added an additional level of detail by also analyzing the regional responses, since the relevance of processes varies among the different regions and biomes. Furthermore, we assessed the consequences more systematically. We performed modeling experiments in which assumptions were changed on the response to temperature, moisture and CO_2 conditions, along with changes in the migration ability of biomes under climate change. The migration ability has been included because land-cover changes have a direct effect on the C cycle through different biome characteristics (e.g. lifetimes of different C pools) and modifications in biophysical characteristics (e.g. albedo).

We first describe the IMAGE 2 model used – focusing on processes that affect the biome distribution and the C cycle – and then the baseline results. This is followed by a specification of the different experiments. In the subsequent result section we emphasize the regional relevance of the different processes. Finally, our approach and results are compared with other studies to allow a synthesis of consistent conclusions.

4.2 Methodology

4.2.1 The IMAGE-2 model

IMAGE 2 (Integrated Model to Assess the Global Environment) is a multi-disciplinary, integrated assessment (IA) model designed to simulate the long-term dynamics of global environmental change, including climate and land-use change. The model is global in application, where all land-related calculations have geographically explicit grid dimensions (i.e. 0.5^0 longitude by 0.5^0 latitude). Each grid cell is characterized by its climate (i.e. temperature, precipitation and cloudiness), soil type, and land-cover (biome or agriculture). IMAGE 2 consists of various sub-models with interactions and feedbacks explicitly included (Figure 4-1). Since the model has been extensively documented (Alcamo *et al.*, 1998; MNP, 2006), we will present only the elements relevant for the C cycle, including land-use changes.

Regional trends in wealth, demography, and technology (improvement) determine in IMAGE 2, for example, the demand for food, fodder, biomass, timber, or C sequestration and resulting land resources in 18 regions around the world. To satisfy these demands, IMAGE 2 integrates submodels for crop production, land-use and land-cover changes, along with the terrestrial C cycle. Changes in production of or demand for products result in changes in land use and related land-use emissions of various greenhouse gases (GHGs) into the atmosphere. The IMAGE 2 atmospheric and ocean submodel simulates changes in atmospheric composition (e.g. CO_2), and subsequently the climate. This is done by using the land-use and energy emissions and by taking the oceanic and terrestrial C uptake, and atmospheric chemistry, into consideration. When climate changes, the distribution and productivity of biomes and agriculture change too, affecting the terrestrial C cycle. The climatic changes are also employed by specific impact sub-models for sea-level rise and land degradation.

The effects of changes in land use and climate on the terrestrial C cycle are computed with the terrestrial C-cycle model of IMAGE 2 (Klein Goldewijk *et al.*, 1994; Van Minnen *et al.*, 2000; Leemans *et al.*, 2002). The driving force of this model is Net Primary Productivity (NPP), which is the photosynthetically fixed C in plants minus C losses due to plant respiration (Equation 1).

Equation 1 $$NPP_{\mathrm{j}}(t) = NPPI_{\mathrm{l,i}} \sum_{m=1}^{12} \left(\left[CF_{\mathrm{j,m}}(t) \right] \frac{f_1(T_{\mathrm{j,m}}(t), l_{\mathrm{j}})\, f_2(SWS_{\mathrm{j,m}}(t))}{AF_{\mathrm{l_j}}} \right)$$

$$AF_{\mathrm{l_j}} = \frac{\sum_{i \wedge i \in l} \left(f_1(T_{\mathrm{i,m}}(1970), l_{\mathrm{i}})\, f_2(SM_{\mathrm{i,m}}(1970) \right) area_{\mathrm{i}}}{\sum_{i \wedge i \in l} area_{\mathrm{i}}}$$

where:

$\beta_{ini:}$	Initial CO_2 fertilization factor, used for all land-cover types and month
NPP	Net primary production (Mg C km^{-2})
NPPI	Mean NPP of one land-cover type in 1970 (Mg C km^{-2})
CF	CO_2 fertilization factor (-) (see Equation 2)
T	Monthly temperature (^{o}C)
SWS	Monthly soil-water status (%)
f_1 and f_2	Multipliers (-) for direct temperature effect and water availability, respectively on plant growth
AF	Normalization factor to 1970 average (-)
area	Grid-cell area (km^2).

Indices include *t*, year (1970–2100); *j*, grid-cell number; *m*, month (1–12); *l*, land-cover type (1–20) and *i*, index of all grid cells covered by one land-cover type in 1970 (*i* is a subset of *j*).

Soil respiration is the oxidation of soil C (i.e. litter, humus and charcoal), resulting in a C flux into the atmosphere. This flux depends on the C stocks in different soil compartments, their turnover rates and environmental conditions. Net Ecosystem Production (NEP) represents the net C flux between the atmosphere and terrestrial ecosystems. It is simulated in IMAGE 2 by the NPP flux minus soil respiration. All these C fluxes are calculated on a monthly basis, while the carbon pools are updated annually.

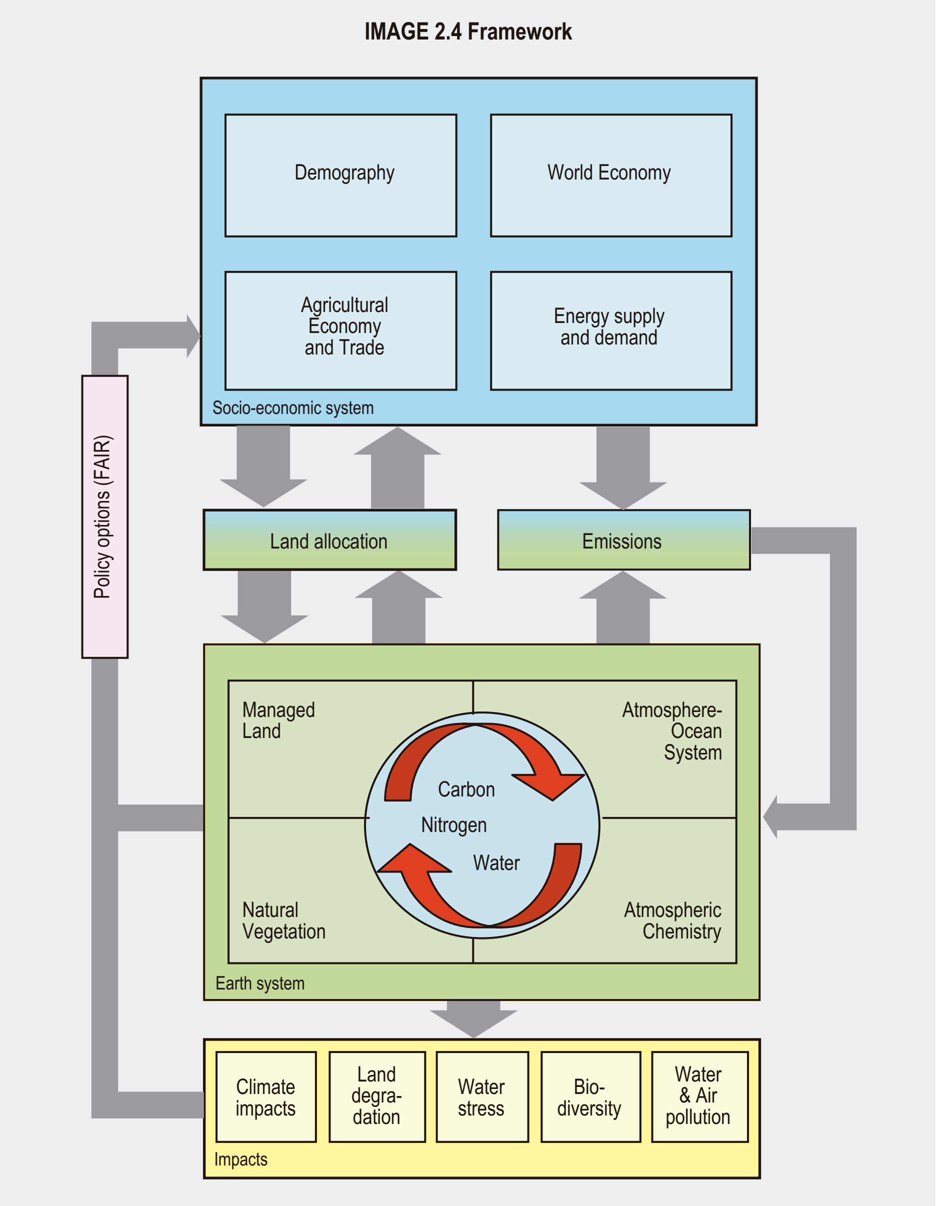


Figure 4-1 The structure of the IMAGE-2 model.

The IMAGE-2 C-cycle model includes various environmental feedback processes that alter NPP, soil respiration and thus NEP. Some processes increase NEP (and lower CO_2 concentration, negative feedback), while others cause a decrease (positive feedback). The feedback processes include the effect of atmospheric CO_2 (Equation 2), soil moisture and temperature through the use of biome specific-response functions. Furthermore, NPP depends in IMAGE 2 on land-cover history.

Equation 2

$$CF_{i,m} = 1 + \beta_{i,m} * \ln(\frac{[CO_2]_t}{[CO_2]_{1970}})$$

$$\beta_{i,m} = \beta_{ini} * f_1(T_{i,m}, SWS_{i,m}) * f_2(nut_i, sp_i, alt_i)$$

where:

$\beta_{ini:}$	Initial CO_2 fertilization factor, used for all land-cover types and month
$f_1(T_{i,m}, SWS_{i,m})$:	Multiplier for temperature “T” and soil moisture “SWS” (-)
$f_2(nut_i, sp_i, alt_i)$:	Multiplier for nutrient availability “nut”, species characteristics “sp” and altitude “alt” in grid cell “i” (all constant over time)
$[CO2]_t$ & $[CO2]_{1970}$:	Atmospheric CO_2 concentration in year *t* and 1970, respectively (ppm)

The IMAGE-2 terrestrial C-cycle model deals consistently – both in time and space – with the effects of four different land-cover transitions on the C pools and fluxes: (i) natural biome towards cropland, pastureland, biofuel or C plantations; (ii) agricultural land to natural biome due to the abandonment of agricultural land; (iii) forests to “re-growth forests” because of timber extraction and (iv) conversions from one biome to another because of climate change. Time lags due to limiting migration abilities of species and the rate of climate change are explicitly considered with regard to the latter conversion (Van Minnen *et al.*, 2000). For example, we assume that grasses grow fast and are widely dispersed, so will migrate more rapidly than tree species.

4.2.2 Scenario assumptions

A number of scenario experiments were performed with IMAGE 2 to analyze the consequences of uncertainties in various biogeochemical and biogeograhical processes for the C cycle. The experiments use the IPCC SRES A1b scenario as a baseline (Nakicenovic *et al.*, 2000). A1b represents an intermediate scenario in terms of anthropogenic drivers and, consequently, GHG emissions and deforestation. For example, the global CO_2 emission in 2100 is 17.6 Pg C yr^{-1} in the range of 6.2 and 30.9 Pg C yr^{-1}. In the IMAGE-2 implementation of A1b, we obtained a consistent series of land-use patterns, atmospheric CO_2 concentrations, and global and regional climate change for the period 2000-2100 (Table 4-1). The effect of the emissions on global climate is quantified by using a medium climate sensitivity of 2.5 ^{o}C for a doubling of CO_2 concentration relative to the pre-industrial era. Regional temperature and precipitation changes are derived from downscaling global values using the Hadley Centre (*HadCM2*) climate model (Figure 4-2). The effects of using alternative climate models and climate sensitivities can be found in Leemans *et al.* (2002).

All experiments except the baseline assume a constant land-use pattern. Changes in natural biomes as a result of climate change remain possible. Although the IMAGE-2 model is explicitly designed to deal with changes in land use, such changes are excluded here in order to focus on simulating the consequences for the terrestrial C cycle as such. With land-use change, an experiment resulting in a lower CO_2 concentration, for example, could result in more land use, compensating a lowered agricultural production. Consequently, higher CO_2 emissions could result. Furthermore, without land-use change, our results are more comparable with other studies, which seldom consider land-use change. However, because of our explicit aim of comparing the relative importance of biogeochemical and biogeographical processes for the C cycle with that of land-use change, we show the A1b baseline results with and without considering land-use changes. More information on the role of land-use changes can be found in Leemans *et al.* (2002), Schaeffer *et al.*(2006) and Van Minnen *et al.* (2008).

Table 4-1 Atmospheric and climate characteristics of the A1b baseline in 2050 and 2100 in combination with all feedbacks using the HadCM2 climate model for downscaling climate information (assuming constant land use beyond 2000)

	2050	2100
Atmospheric CO_2 (ppm) (in 2000, 325 ppm)	527	696
Global avg. temperature change, incl. oceans	1.9	3.2
Global avg. temperature change, land-based	2.0	3.9
Global avg. precipitation change, land-based	26	55
Avg. temp. change tropical forests	2.0	3.6
Avg. temp. change savannas	2.1	3.9
Avg. temp. change scrubland	2.0	3.8
Avg. temp. change boreal forests	2.7	4.2
Avg. prec. change tropical forests	51	99
Avg. prec. change savanna	15	37
Avg. prec. change scrubland	-22	-37
Avg. prec. change boreal forests	44	84

Both temperature and precipitation changes are compared to 1961–1990 averages (in °C and mm.yr^{1}, respectively)

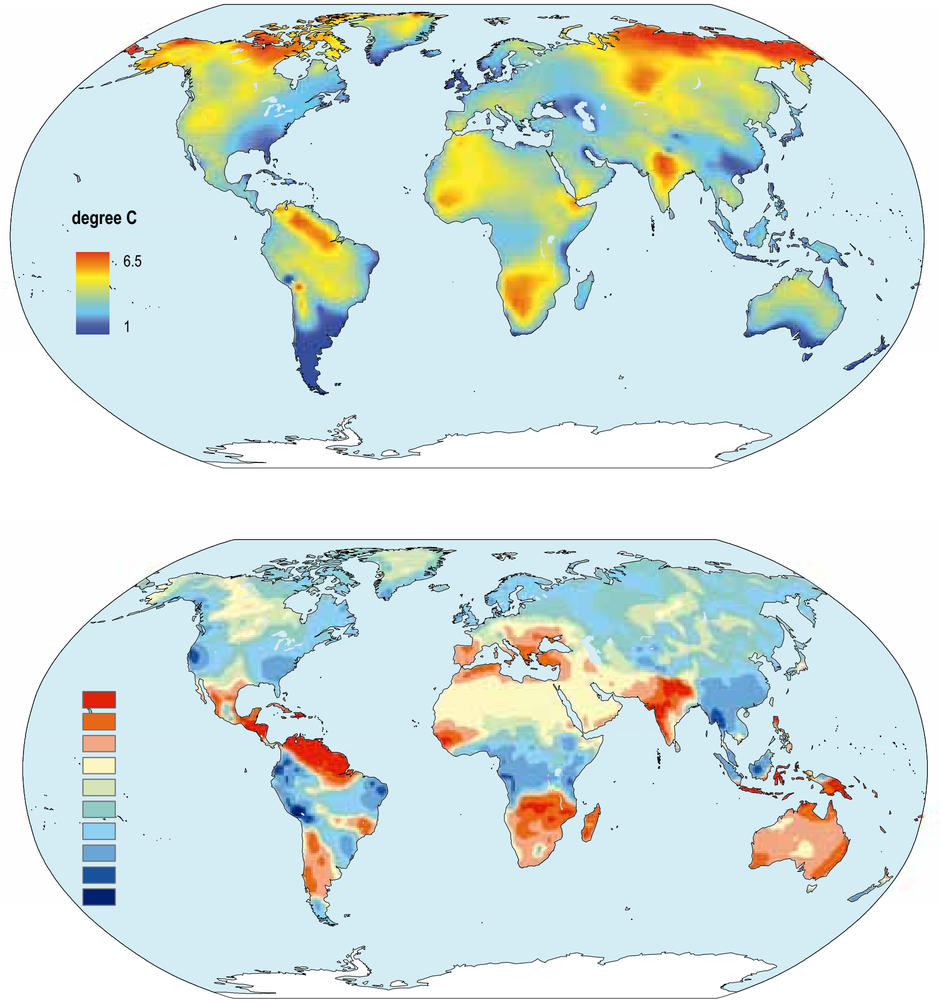


Figure 4-2 Projected changes in temperature (top) and precipitation (bottom) in 2100 under the A1b scenario using the IMAGE-2 model without land-use changes. Global changes scaled by the HadCM2 climate model (temperature change in oC, precipitation change in mm.yr-1, both compared to the 1961–1990 average).

4.2.3 Experimental design

We defined 13 alternative scenario experiments, all variants to the A1b baseline. The experiments make different assumptions about biogeochemical processes and the migration ability of plant species in response to changing CO_2 levels in the atmosphere, moisture availability, and temperature (Table 4-2). Note that this analysis is a quantification of uncertainty ranges based on broad assumptions. The experiments are grouped into five main sets.

Table 4-2 Significance of experiments, where negative feedbacks are indicated by (-), positive feedbacks by (+)

Name of experiment[1]	Description
NoLUC	Baseline experiment, according to the IPCC A1b scenario based and using HadCM2 climate model, excluding land-use changes
WithLUC	A1b SRES baseline scenario, including changes in land use
Biogeochemical feedbacks	
Set 1: CO_2 fertilization	
(-) NoFert	Exclude the NPP response to changing CO_2 levels (=No CO_2 fertilization)
(-) 50Fert	Limit the C02 fertilization to 50% of the original response
(-) ConstFert	Maintain the C02 fertilization effect in each grid cell at its value in year 1995
Set 2: NPP response to climate	
(-) ConstTempNPP	Maintain the NPP response to changing temperature in each grid cell at its 1995 value
Set 3: Soil respiration	
(-) NewSoilResp	Replace the soil respiration equation by an Arrhenius equation (Lloyd & Taylor, 1994)
(+) ConstResp	Maintain the soil respiration response to changing climate (i.e. moisture and temperature) conditions at the 1995 value in each grid cell
Set 4 Biogeographical feedbacks	
(-) NoMigration	Exclude migration abilities as a response of land-cover types to climate change
(+) FastMigration	Consider infinite migration rates, leading to instantaneous changes in land cover
Set 5 Combined experiments	
NoFeedbacks	Exclude all feedbacks (i.e. No CO_2 fertilization, No temperature & moisture responses, no migration)
OnlyTempNPP	Exclude all feedbacks except the temperature effect on NPP
OnlyCResp	Exclude all feedbacks except the climate (temperature and moisture) effect on soil decomposition
OnlyTempNPP_Resp	Exclude all feedbacks except the temperature effect on NPP, and the temperature and moisture effect on soil decomposition
ConstClim	Maintain all temperature and moisture sensitivities at 1995 values in each grid cell

In the first set of experiments we modified the NPP sensitivity to changes in atmospheric CO_2. This was implemented by changing the initial CO_2 fertilization factor (i.e. β_{ini} in Equation 2). As default, IMAGE 2 assumes β_{ini} to be 0.7, implying a maximum of 70% NPP increase at a doubled CO_2 concentration. Because of the two multipliers for climatic and local conditions (Equation 2), the actual fertilization factor $\beta_{i,m}$ is lower than 0.7. The global value in 2100, for example, was 0.43, 0.2 for boreal forests, and 0.51 for tropical forests (Brinkman *et al.*, 2005). The strength of the CO_2 fertilization effect is still controversial, especially in natural vegetation and over continental scales. Harvey (1989) and Alexandrov *et al.* (2003) propose a value between 0.35 and 0.6, whereas Cao & Woodward (1998) expect a saturation of the effect in the longer term. Heath *et al.* (2005) and Körner *et al.* (2005) even question the existence of long-term and large-scale CO_2 fertilization due to other constraints. Likewise, experiments showed a growth stimulation due to enhanced CO_2, but less than previously assumed on physiological grounds (Novak *et al.*, 2004, Norby *et al.*, 2005). In order to evaluate the consequences of this uncertainty, we modified the β_{ini} in three different ways (Table 4-2).

The NPP response to changing temperature was evaluated in the second set of experiments (see Table 4-2). This response is implemented in the IMAGE-2 model by an optimum curve (Woodward *et al.*, 1995; Larcher, 2003). In the experiment, the effect of temperature on NPP was assumed to be constant after 2000 (ConstTempNPP).

In the third set we focused on soil respiration (Table 4-2). Uncertainties in this process may have considerable consequences for the C cycle because of the large amounts of C stored in the soil with a mixture of decomposition rates (Davidson & Janssens, 2006). The main drivers of soil decomposition are temperature and moisture availability (Knorr *et al.*, 2005; Davidson & Janssens, 2006). Especially the relationship between temperature and soil decomposition is an issue of current scientific discussions (see reviews by Knorr *et al.*, 2005 and Davidson & Janssens, 2006). In principle, microbial activity and thus soil decomposition increase exponentially with increasing temperature (Waring & Running, 1998). However, this does not necessarily imply that the decomposition increases continuously, especially on a regional scale under global warming. Initially, increased decomposition rates may return to pre-warming rates within a limited number of years due to adaptation of the micro-organisms (Giardina & Ryan, 2000). In one experiment, we kept soil respiration rates constant from the year 2000 onwards, ignoring changes in temperature or moisture availability (ConstRes). In the experiment NewSoilResp, we replaced the default optimum curve of temperature on soil decomposition by the Arrhenius equation of the LPJ model (Sitch *et al.*, 2003). The alternative Arrhenius equation describes an exponential response of soil respiration to increasing temperatures. Particularly beyond the optimal temperature values, this leads to higher soil respiration rates when compared to the standard IMAGE-2 approach.

In the fourth set of experiments we assume alternative migration rates, compared to Van Minnen *et al.* (2000) (Table 4-2). Migration of species as a response to climate change is poorly understood (Araujo *et al.*, 2004). Higher migration rates than those derived from past records (Davis, 1981; Huntley & Webb) may be needed to cope with climate change as anticipated in different scenarios (Leemans & Eickhout, 2004). The rates will, however, not be infinite and differ between species, as the geographical reorganization of ecosystems is a slow process (Huntley & Webb, 1989). To assess the consequences of the uncertainty in migration rates for the terrestrial C cycle, we used two extreme cases (Table 4-2). A consequence of ignoring the possibility of species migration (NoMigration) is that it leads to degraded biomes. In the FastMigration experiment, biome changes may occur instantaneously, since migration rates are assumed to be infinite. This results in, for example, immediate pole-wards shifts of forests under global warming.

Finally, five combined experiments were included to assess interactions between processes and to distinguish between the overall role of climate change on the one hand, and CO_2 response on the other (Table 4-2). The latter allows a comparison with other studies (e.g. Cramer *et al.*, 2001; Joos *et al.*, 2001; Friedlingstein *et al.*, 2003) that often focus on “climate only” and “CO_2 only”. Furthermore, the non-climate-driven development of the biome could be assessed by excluding all feedbacks (*NoFeedbacks*). For these combined experiments, processes were grouped into positive or negative feedbacks using the consequences for the atmospheric CO_2 concentration as a criterion. Note that this criterion does not automatically imply a similar effect on all terrestrial C-cycle fluxes and pools.

4.3 Results

4.3.1 Global analysis

Despite identical fossil-fuel related CO_2 emissions across the experiments, global terrestrial C fluxes and pools differ considerably in space and time (Table 4-3, Figure 4-3).

Land use has had a considerable effect. This is illustrated by comparing the *NoLUC* experiment –where the projected NEP increases from about 2.5 Pg C yr^{-1} in the 1990s to about 6.8 Pg C yr^{-1} around 2060, followed by a decline – with the *WithLUC* experiment – where the NEP flux is projected to increase continuously up to 6.6 Pg C yr^{-1} in 2100 due to increasing abandonment of agricultural land.

The comparison of the different feedback processes has shown a difference in projected global NEP of almost 8 Pg C yr^{-1} in 2100 across the experiments (Table 4-3). NEP reaches 7.2 Pg C yr^{-1} in 2100 if we assume a constant soil decomposition (*ConstResp*), whereas the terrestrial biosphere turns into a (small) C source if we consider only the climate effect on soil decomposition (*OnlyCResp*).

Evaluating the relative importance of individual feedbacks has shown that CO_2 fertilization is the dominant negative feedback process, and the soil decomposition response to changing temperature and moisture is the most relevant positive feedback (Figure 4-3; Table 4-3, set 1). If we ignore, for example, CO_2 fertilization (*Nofert*), the global NPP and NEP fluxes are projected to increase up to 2100 only 5.4 Pg C yr^{-1} and 0.7 Pg C yr^{-1}, respectively, compared to 31.5 Pg C and 5.3 Pg C in the baseline (Figure 4-3). Note that the parameter setting of the CO_2 fertilization in IMAGE 2 is at the high end in the literature. But even if we assume a 50% lower CO_2 sensitivity (*50Fert*), the C pools and fluxes are projected to change more than with climate-induced feedback processes (Table 4-3, Table 4-4).

Despite the projected prominent role of CO_2 fertilization, climate-driven feedbacks still have considerable impacts on the biome distribution, and related C pools and fluxes (Figure 4-3, Table 4-3 sets 3 & 4). But these effects are more difficult to understand. Ignoring, for example, all climate feedbacks (*ConstClim*) led to a projected C storage in the vegetation that increases 7% less than in the baseline (up to 2100), whereas soil C storage shows only a 1% difference. These limited changes are the result of the counteracting response of NPP and soil respiration on climate change. This can be illustrated by evaluating individual processes (Table 4-3, set 2 & 3). Ignoring, for example, changes in the soil decomposition (*ConstResp*) has shown a biosphere that shifts from a C sink into a source around 2050 (Table 4-3). Likewise, the global NEP in 2100 is projected to be about 25% lower than in the baseline if we keep the NPP response to changing temperatures constant (*ConstTempNPP*) or exclude natural ecosystem changes (*NoMigration*) (Figure 4-3, Table 4-5 set 4). The latter decrease results from degrading biomes under changing climate conditions when migration is allowed.

Note that the combined experiments (e.g. *NoFeedback*) have resulted in smaller effects than the sum of individual responses (Table 4-3). For the global NEP change in 2100, for example, the sum of the individual effects is -7 Pg C yr^{-1} compared to the baseline, whereas it decreases by -5 Pg C yr^{-1} in the case where all feedbacks are simultaneously excluded. This shows the importance of interactions between the feedback processes.

Table 4-3 **Terrestrial C pools and fluxes for the different experiments (A positive flux represents a biospheric uptake)**

	NPP (Pg C.yr^{1}) ’70–‘80avg=57-58 2000 = 58 – 61		NEP (Pg C yr^{1}) ’70–‘80avg=0–0.5 2000= 0.5 – 2.7		Living biomass (Pg C) ’70–‘80avg=537 2000=450 – 550		Soil biomass (Pg C) ’70–‘80avg=1572[1] 2000=1493–1600	
	2050	*2100*	*2050*	*2100*	*2050*	*2050*	*2050*	*2100*
NoLUC	77	89	6.4	5.9	641	779	1684	1842
WithLUC	77	86	6.3	6.6	535	613	1675	1801
Biogeochemical feedbacks								
Set 1: CO_2 fertilization								
NoFert	62	64	1.4	1.3	562	602	1583	1585
50Fert	70	78	4.1	3.9	606	701	1639	1729
ConstFert	65	67	1.7	1.4	582	627	1616	1627
Set 2: NPP response to climate								
ConstTempNPP	75	85	5.2	4.6	629	743	1669	1787
Set 3: Soil respiration								
NewSoilResp	77	90	5.7	5	642	784	1699	1813
ConstResp	76	88	7.4	7.2	639	768	1710	1934
Set 4: Biogeographical feedbacks								
NoMigration	76	86	5.5	4.4	632	738	1676	1800
FastMigration	77	89	6.8	6.3	650	793	1690	1880
Set 5 Combined experiments								
NoFeedbacks	58	57	0.8	0.9	531	533	1585	1602
OnlyTempNPP	60	62	2.2	2.4	547	573	1603	1666
OnlyCResp	58	57	-0.4	-0.5	531	533	1555	1502
OnlyTempNPP_Resp	60	62	0.9	0.8	547	574	1573	1563
ConstClim	74	84	5.9	5.4	623	726	1692	1860

[1] Excepting A1b-NewSoilResp experiment, where the initial soil biomass is 1598 Pg C

Table 4-4 Atmospheric and climate characteristics for 2050 and 2100

	Atmospheric CO_2 concentrations (ppmv)		Global-mean temperature change compared to 1961–1990 average (°C)		Global-mean precipitation change compared to 1961–1990 average ($mm.yr^{-1}$)	
	2050	*2100*	*2050*	*2100*	*2050*	*2100*
NoLUC	527	696	1.9	3.2	26	55
WithLUC	560	749	2	3.4	29	58
Biogeochemical feedbacks						
Set 1: CO_2 fertilization						
NoFert	590	854	2.1	3.7	29	62
50Fert	555	765	2	3.4	29	58
ConstFert	572	831	2	3.6	29	62
Set 2: NPP response to climate						
ConstTempNPP	537	729	1.9	3.3	26	51
Set 3: Soil respiration						
NewSoilResp	532	714	1.9	3.3	26	55
ConstResp	519	666	1.9	3.1	26	55
Set 4 Biogeographical feedbacks						
NoMigration	533	726	1.9	3.3	26	55
FastMigration	523	685	1.9	3.2	26	51
Set 5Combined experiments						
NoFeedbacks	600	873	2.2	3.7	33	62
OnlyTempNPP	588	833	2.1	3.6	29	62
OnlyCResp	611	911	2.2	3.8	33	66
OnlyTempNPP_Resp	599	872	2.2	3.7	29	62
ConstClim	531	708	Constant climate			

Table 4-5 Changes in land-cover distribution (100% implies no change compared to 2000)

	Total forest area		Boreal forest		Tropical rain forest		Savanna		Grassland	
	2050	*2100*	*2050*	*2100*	*2050*	*2100*	*2050*	*2100*	*2050*	*2100*
NoLUC	103	109	104	114	98	96	93	86	94	90
WithLUC	98	110	104	114	80	72	67	93	84	96
Biogeochemical feedbacks										
Set 1: CO_2 fertilization										
NoFert	103	109	105	115	97	94	90	84	94	90
50Fert	104	110	104	115	98	95	91	85	94	90
ConstFert	104	110	104	115	98	94	91	84	94	90
Set 2: NPP response to climate										
ConstTempNPP	102	105	104	114	98	95	92	85	101	102
Set 3: Soil respiration										
NewSoilResp	103	109	104	114	98	95	93	85	95	90
ConstResp	103	109	104	113	98	95	93	86	94	90
Set 4: Biogeographical feedbacks										
NoMigration	100	100	100	100	100	100	100	100	100	100
FastMigration	107	114	99	88	99	97	85	70	90	79
Set 5 Combined experiments										
NoFeedbacks	102	105	103	113	97	94	107	112	101	102
OnlyTempNPP	102	105	103	113	97	94	108	112	101	102
OnlyCResp	102	105	103	113	97	94	108	113	101	102
OnlyTempNPP_Resp	102	105	103	113	97	94	107	112	101	102
ConstClim	101	104	99	101	99	100	91	79	94	89

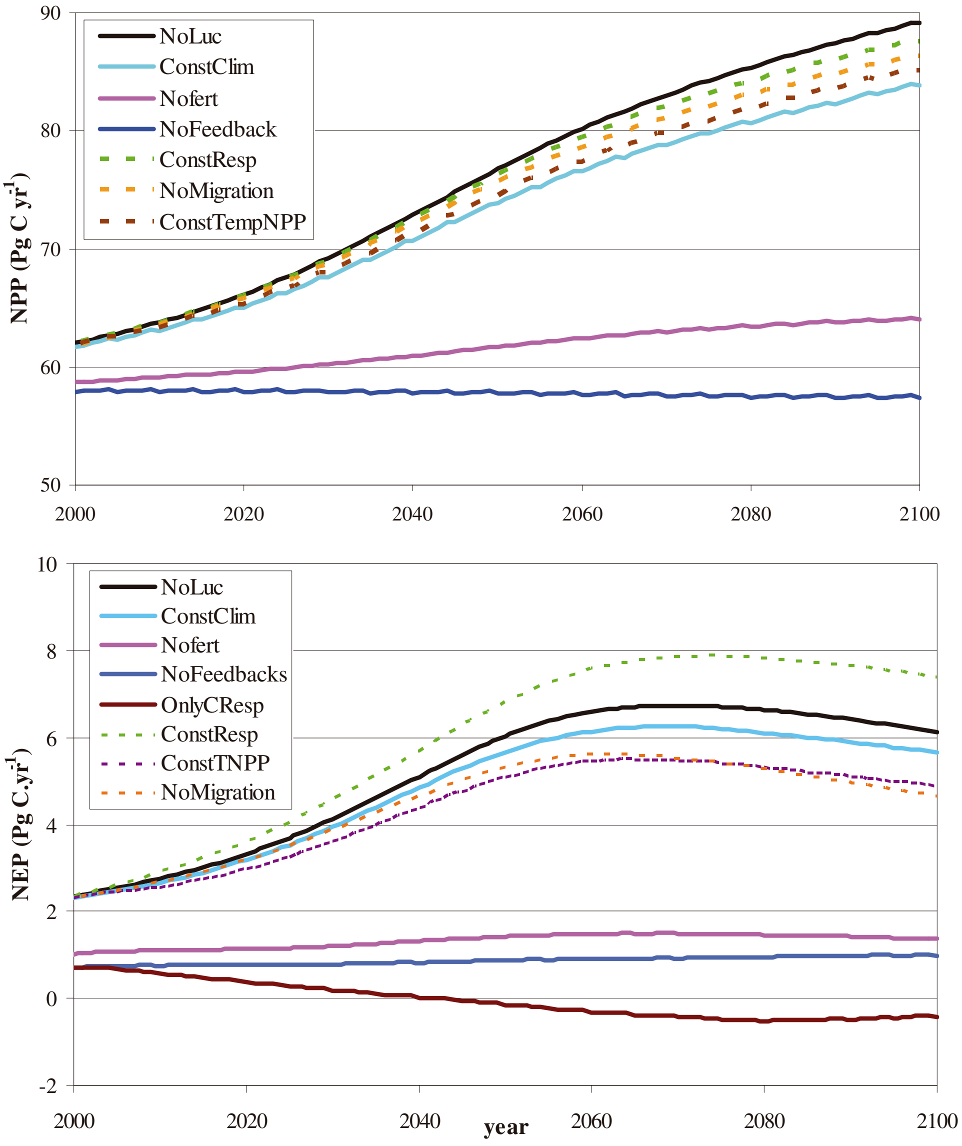


Figure 4-3 **Global NPP (top) and NEP (bottom) fluxes (in Pg C yr^{-1}) for experiments that define the range. Solid lines show the combined experiments of baseline and no feedbacks, Nofertilization (=only climate) and constant climate (=CO_2 only). Dashed lines show the individual feedback processes that determine the "constant climate" effect.**

4.3.2 Regional differentiation

The projected changes in C pools and fluxes vary considerably across the regions (Table 4-6, Figure 4-4). In the baseline (i.e. *NoLUC*), the NEP of certain biomes is projected to decrease between 2050 and 2100, whereas it continuously increases in others. The decrease is often caused by a stabilizing NPP – due to above-optimal temperatures and more droughts – while soil respiration rates are projected to increase.

Tropical forests have contributed most to the projected changes in C fluxes (Figure 4-4, Table 4-6). They have been responsible for 27–30% of the global NPP and NEP increase between 2000 and 2050, with the largest increases for tropical forests in Africa. CO_2 fertilization is the most important driver of this increase. Between 2050 and 2100 the area-based NEP of tropical forests is projected to decrease by 21% (Table 4-6), mainly due to a smaller uptake of the tropical forests in South America. The reduced uptake is caused by increasing soil respiration, with NPP stabilization. Soil respiration is projected to increase (and NEP decreases) even more if the alternative Arrhenius equation for the temperature response is used (i.e. *NewSoilResp*). This shows, especially for tropical forests, the need for a better understanding of soil response to climate change.

Other biomes that respond considerably to the changing environmental conditions are agriculture, grassland, and boreal forests (Figure 4-4, Table 4-6). The NPP of agriculture, mainly in the USA, South America and FSU, has been projected to benefit especially from changes in atmospheric CO_2. The NPP of boreal forests, initially 8.4 Pg C.yr^{-1}, is projected to increase in the baseline (i.e. NoLUC) by 70% up to 14.1 Pg C yr^{-1} in 2100. This increase is partly due to a 14% expansion of the boreal forest area and partly to an increase in the area-based NPP of boreal forests (i.e. from 5.1 Mg C .ha. yr^{-1} up to 7.7 Mg C .ha^{-1}.yr^{-1}, Table 4-6). The NPP of grassland (or steppe) areas around the world is projected to increase by about 50%, whereas the NEP nearly doubles between 2000 and 2060, followed by a 25% decrease in the 2nd half of this century (Figure 4-4). The decrease is caused by a shrinking area and a continuous response of soil decomposition to climate change. Finally, we projected a considerable increase in the C sink of some other biomes at high latitudes. However, the contribution to the overall C cycle has been limited due to the small extent.

Regionally, the differences between the experiments are larger than globally (Table 4-5, Table 4-6, Figure 4-4). Without any feedback process (*NoFeedbacks*), NPP and NEP of most land-cover types have been projected to remain constant, while savanna has become a small source of C.

Carbon dioxide (CO_2) fertilization is also the dominating feedback process for terrestrial C dynamics on the regional scale (Table 4-6, Figure 4-4). Although tropical forests in general kept a small C sink, without CO_2 fertilization (*Nofert*) (Figure 4-4), tropical forests in South America and Asia are estimated as becoming a source of C. The decreased C storage in tropical forests is caused by above-optimal temperatures (Table 4-6) and decreasing area (Table 4-5).

Next to CO_2 fertilization, the most important climate feedback for the terrestrial C cycle in tropical regions is the temperature effect on soil decomposition, especially in the long term. Outside the tropical regions other feedback processes are projected to become more relevant (Figure 4-4, Table 4-6). The projected 60% increase of the area-based NPP of boreal forests in 2100, for example, is the yield of a combination of all processes. These forests are being projected as a possible future C source, if we consider only the temperature effect on soil decomposition (*OnlyCresp*, Table 4-6). The C dynamics in grassland areas around the world have also responded to changes in CO_2 and climate. Temperature changes have been responsible for approximately one-third of the projected NPP increase between 2000 and 2100. Since soil decomposition of grassland areas responds similarly (quantitatively) to changes in temperature and moisture availability (Figure 4-4), NEP changes in grasslands have been mainly triggered by CO_2 fertilization. Only in the case of no migration, grasslands have become degraded, resulting in decreased NEP fluxes and soil C pools (Figure 4-4).

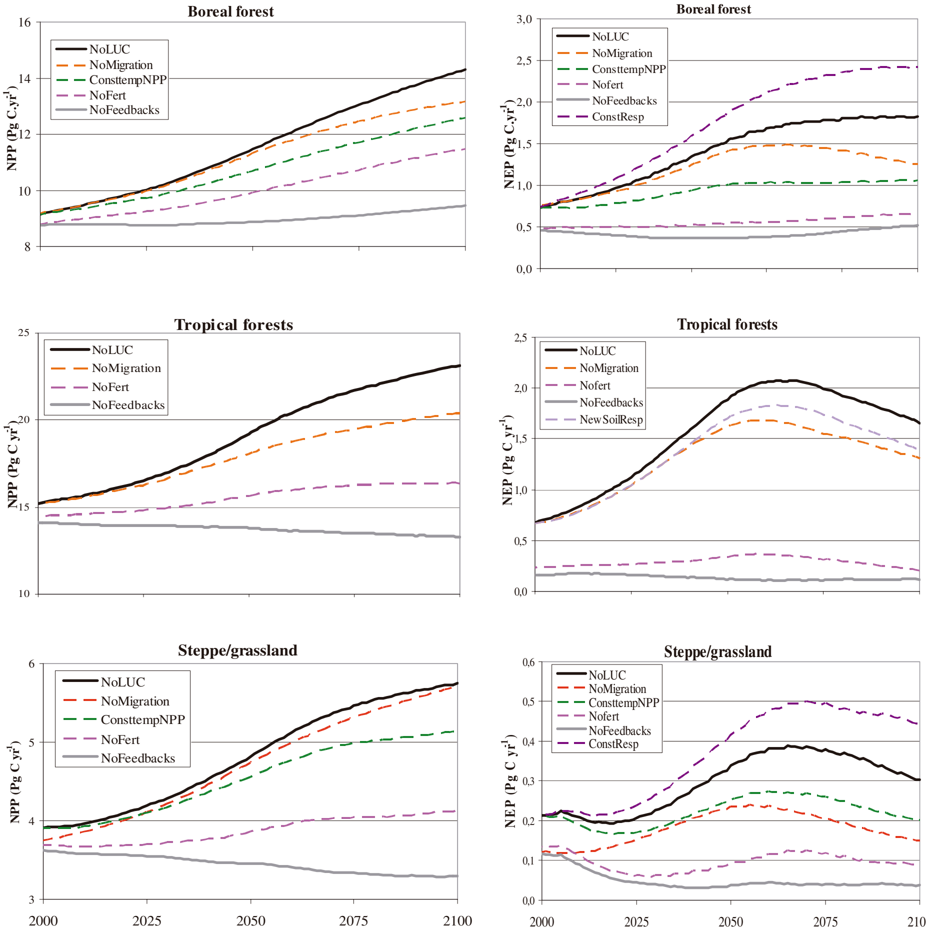


Figure 4-4 **NPP (left) and NEP (right) fluxes for the most relevant biomes (unit: Pg C.yr^{-1}). The lines show the range reflected in the experiments.**

Alternative migration assumptions have led to considerably different projections of the C pools and fluxes in savanna, grassland, and particular boreal forests areas (Figure 4-4). The effect on the extent of boreal forest ranges from a 12% reduction (assuming an infinite migration (*fastmigration)* to a 15% increase in many other experiments. Because of the considerable effect on the distribution of boreal forests, the net effect on their total NPP is even larger than the effect of CO_2 fertilization (Figure 4-4).

The projected strong effect of climate on the boreal forest distribution and thus the C dynamics is, firstly, caused by the larger projected changes in climate in boreal regions than being projected for low or mid-latitudes (Table 4-1). Secondly, boreal forests are highly responsive to changes in climatic conditions. In general, the invasion of tundra areas in the north is expected to occur faster than replacement in the south by other forest types (Van Minnen *et al.*, 2000). This difference diminishes if no migration restrictions are assumed, explaining the net decrease in the boreal forest area in the *fastmigration* experiment.

Table 4-6 Simulated area-based NEP fluxes for different biomes across the world (in g.m^{-2}.yr^{-1})

	Boreal forest (initial[1]=17)		Tropical Rain forest (initial[1]=14)		Savanna (initial[1] = -2)		Scrubland (initial[1] = 7)		Grassland (initial[1] = 10)	
	2050	*2100*	*2050*	*2100*	*2050*	*2100*	*2050*	*2100*	*2050*	*2100*
Base	93	101	157	171	74	46	64	30	44	30
NoLUC	87	92	130	103	49	27	44	44	40	33
Biogeochemical feedbacks										
Set 1: CO_2 fertilization										
NoFert	29	33	15	11	3	-3	0	5	12	10
50Fert	61	66	78	64	28	14	25	27	28	23
ConstFert	35	36	19	13	6	-3	5	8	13	11
Set 2: NPP response to climate										
ConstTempNPP	53	53	128	110	43	26	36	36	27	21
Set 3: Soil respiration										
NewSoilResp	82	86	112	83	42	20	42	41	40	31
ConstResp	112	126	132	101	52	29	51	50	54	52
Set 4: Biogeographical feedbacks										
NoMigration	82	70	128	103	36	23	24	20	25	15
FastMigration	108	126	132	106	39	28	47	45	42	35
Set 5 Combined experiments										
NoFeedbacks	21	28	14	16	-9	-13	3	3	6	4
OnlyTempNPP	57	69	19	15	-4	-10	10	8	20	21
OnlyCResp	-9	-8	8	12	-14	-17	-6	-3	-8	-11
OnlyTempNPP_Resp	28	31	13	10	-8	-14	3	2	6	3
ConstClim	76	73	127	103	47	28	42	37	37	37

[1] Initial implies the average of period 1970–1980

4.4 Discussion

In the previous section we presented results of an experimental design in which C-cycle processes were evaluated in order to assess the uncertainty in the ecosystem response to climate change. We are aware that not all processes that might be relevant for the terrestrial C cycle are included in IMAGE 2. For example, disturbances such as fire and pests are not included, while they may have considerable impacts in the tropical (Cramer *et al.,* 2004) and boreal regions (Li *et al.,* 2003). Likewise, we did not account for biogeophysical effects such as changes in albedo caused by land-use change. Some of these processes will be included in (near-term) future IMAGE versions. Here, we want to emphasize the robust findings of the analysis presented, and include these in a broader discussion and comparison with other studies (Table 4-7).

4.4.1 The applicability of the IMAGE-2 C-cycle model

Qualitatively, many models including IMAGE 2 –especially when excluding land-use changes– project an increase in NPP during the 21st century, whereas the NEP increases in the first half of the 21st century, followed by a decline (Cramer *et al.*, 2001; Friedlingstein *et al.*, 2003; Berthelot *et al.*, 2005; Schaphoff *et al.*, 2006). However, in our baseline we did not project a shift from a global terrestrial sink to a C source, as shown in some model exercises for the 2050–2100 period (e.g. Cox *et al.*, 2004). In these studies, the tropics, in particular, have turned into a major source of C due to declining NPP, whereas soil respiration in the rest of the world has increased more than NPP. We have also projected a declining NEP in tropical regions under climate change only (Table 4-6). But the projected decline in the tropics was smaller than seen in other studies; furthermore, it is counterbalanced by increased NEP in other parts of the world, resulting – still – in a global net C sink.

A q*uantitative* comparison of the results presented here with observations and outcomes of other models – such as the more complex Dynamic Global Vegetation Models (DGVM) – shows the global NPP and NEP fluxes in the 1990s to be within the existing ranges (Table 4-7a). Regionally, Li *et al.* (2003) and Krankina *et al.* (2004), for example, reported a contemporaneous NEP of 0.4 Mg C $ha^{-1}.yr^{1}$ and 0.36 Mg C $ha^{-1}.yr^{1}$ for Canadian and Russian boreal forests, respectively, while we show a simulated NEP of 0.4–0.5 Mg C $ha^{-1}.yr^{1}$ and 0.32–0.36 Mg C $ha^{-1}.yr^{1}$, respectively.

With respect to the *projected* C cycle up to the year 2100, the global soil respiration flux and vegetation C pools have been comparable to outcomes of different DGVMs (Table 4-7b). The projected NPP and NEP fluxes for 2050 and 2100 are also within the ranges of other studies –albeit at the high end – while the projected soil biomass exceeds the range. The maximum projected NEP, for example, was 6.8 Pg C yr^{1} (around mid-21st century) compared to 4.6 ± 2.0 Pg C yr^{1} for the average taken across different DGVMs (Cramer *et al.*, 2001) and 3.4 Pg C yr^{1} for different LPJ versions in combination with different climate models (Schaphoff *et al.*, 2006). Likely reasons for these high values are the assumed high sensitivity of NPP to atmospheric CO_2 increases in IMAGE 2, and an underestimation of the soil decomposition response. When assuming only half the CO_2 sensitivity (*50fert*), the projected maximum global NEP flux around 2050 is 4.1 Pg C yr^{1} (Table **4-3**).

Table 4-7 a) IMAGE-2 results presented compared to observations for the 1990s

	IMAGE 2	Literature	Ref.[1]
Total NPP			
(Mg C.yr^{-1})			
Boreal forest	9.1	2.4 – 4.2	2,5,7
Temp. forests	5.2	6.4 – 8.1	2,5,7
Trop. forest	15.0	15.2 – 21.9	1,2,5,7
Grassland & savanna	8.4[2]	14 – 20.5	2,5,7
Area–based NPP			
(Mg C.ha^{-1} .yr^{-1})			
Boreal forests	5.6	1 – 7.5 (avg. 4)	2, 4,5
Temp. forests	6.6	7.1 – 7.9	2,5,7
Tropical forests	12.2	5 – 17.5 (avg. 11)	1,2,5,7
Grassland & savanna	5	1 – 10 (avg. 4.5)	2,5
Global NEP	2.0 (with land use)	1.4 – 2.9	2,3,5,8,9
(Mg C.yr^{-1})	2.3 (without land use)		
Area-based NEP			
(Mg C.ha^{-1} .yr^{-1})			
Boreal forests	0.32 – 0.5	0.36 – 0.4	4,10
Tropical forests	0.5	0.6 – 0.9	11,12
Global biomass (Pg C)			
Living biomass	548	466 – 830	2,7
Soil biomass	1591	1570 – 2344	2,7
Global area (Mha)			
Forests	4.6	4.2	2,5,7
Grassland & savanna	3.4	3.3 – 4.3	2,5,7

[1] Based on (1)Silver, 1998;(2) WBGU, 1998; (3) Houghton, 2003; (4) Li *et al.*, 2003; (5) Grace, 2004; (6) Nemani *et al.*, 2003. (7) Sabine *et al.*, 2004; (8) Achard *et al.*2002; (9) DeFries *et al.*2002; (10) Krankina *et al.* (2004); (11) Baker *et al.* (2004) (12)Prentice *et al.* (2001);

[2] Excl. rangeland

b) Projected baseline (NoLUC) changes compared to the year 2000 (fluxes in Pg C yr^{-1}; pools in Pg C, concentration in ppm)

	2050			2100			2070–2100 avg[3]
	IMAGE 2	LPJ[1,2]	Combined DGVM[1]	IMAGE 2	LPJ[1,2]	Combined DGVM[1]	LPJ with different climate models
Atm. CO_2 concentration	+151	+110		+320	+472		
Global NPP	+14,8	+13.9	+13.0 (Range 9.6–18.2)	+27.1	+23.6	+22.9 (Range 17.1–32.1)	+14.3 (Range 10 to 21)
Global soil respiration	+10.4	+11.1	+10.8 (Range 7.3–16.1)	+23.6	+21.9	+21.8 (Range 18.0–33.2)	+14.2 (Range 12 to 18.5)
Global NEP	+4.1	+1.6 –3.2	+2.8 (Range 1.6–4.1)	+3.5	+1.1–1.7	+1.5 (Range -1.9 – +5.8)	+0.1 (Range -3.1 to +2.4)
Vegetation pool	+92		+88	+231		+235	+55 (Range -8 to +151)
Soil C pool	+92		+44	+250		+103	-23 (Range -98 to +51)

[1] Based on Cramer *et al.* (2001) and Zaehle *et al.*(2005) for a IPCC IS92e baseline scenario (comparable but not identical to the IPCC A1b scenario used) and the HadCM2 climate model

[2] Sitch *et al.*2005, using the A1b scenario without land-use changes and a link between LPJ and the CLIMBER2 climate model

[3] Schaphoff *et al.* (2006) in combination with the IS92a baseline scenario

4.4.2 The relevance of individual feedbacks

The relevance of the individual feedback processes depends on the scale considered. Globally, the most important source of uncertainty is the physiological response to increasing CO_2 levels in the atmosphere. The impact of CO_2 fertilization alone has a larger effect on the C fluxes than all other feedbacks taken together. Even if we assume a 50% lower CO_2 sensitivity (*50Fert*), CO_2 fertilization remains the dominant process for the terrestrial C cycle on the global scale. The dominant role of the CO_2 fertilization process is partly the results of the counteracting effect of climate on NPP and soil respiration.

Other biogeochemical and biogeographical feedback mechanisms are important, especially regionally. In tropical regions, for example, climate feedbacks are projected to be relevant because of the climate effect on soil decomposition (see the differences among the experiments in set 3 of Table 4-6). The simulated effect has, however, been smaller than estimated by Rayner *et al.* (2005) and Scheffer *et al.* (2006). Different assumptions related to the migration capabilities and the NPP response to temperature changes had large effects on the C pools and fluxes in boreal regions. Regarding migration, the effects are likely to be even larger if biogeophysical responses (i.e. the effect of land cover on the earth's radiation balance and surface roughness) would be included. Betts (2000), Brovkin *et al.* (2006) and Schaeffer *et al.*(2006) question the effectiveness of new forests in high latitudes as an option for mitigating climate change because of the negative effects on the radiation balance. A similar effect applies to natural land-cover conversions. If the conversion of tundra into boreal forests occurs at a slower rate than currently projected by various models – because of the overestimation of migration abilities or other spatial constraints – this will have consequences for the biogeophysical characteristics of land cover in high latitudes and subsequently the climate. Based on these results, we underline the importance for the C cycle of a good understanding of the migration ability of species to change in climatic conditions.

The dominant role of CO_2 fertilization in determining global C pools and fluxes has also been found in other modeling studies (e.g. Joos *et al.*, 2001; Friedlingstein *et al.*, 2003; Sitch *et al.*, 2005). However, the strength of the CO_2 fertilization effect is still controversial, especially for natural biomes, and over continental scales and long time horizons (Heath *et al.*, 2005). For example, the feasibility of the large increase in terrestrial C uptake (globally, up to 6 Pg C yr^{1} and, regionally an increase from the current 0.3–0.5 up to 0.9 Mg C ha^{-1} yr^{1} in boreal forests) could be overestimated because of the importance of other environmental constraints (e.g. nutrient availability) (Alexandrov *et al.*, 2003; Körner *et al.*, 2005) and ozone (Sitch *et al.*, 2007).

4.4.3 Uncertainties in ecosystem response under different scenarios

Having the C-cycle model presented as being integrated into the IMAGE-2 modeling framework has provided the possibility to compare uncertainties in the terrestrial C cycle responses under different socio-economic and land-use scenarios. Such quantification has been done in two ways. Firstly, we compared results of the baseline experiment (i.e. NoLUC) with the WithLuc experiment, both for the IPCC A1b scenario. This clearly shows robust results, even when land use is also considered (e.g. Table 4-3, Table 4-6).

Secondly, we compared the findings for the A1b baseline scenarios with other scenario applications of IMAGE 2 (Table 8). The variation in atmospheric CO_2 concentration among the experiments presented here for 2100 is about 70% of the variation among IMAGE-2 scenarios (i.e. 245 ppm between the *ConstResp* and *OnlyCResp* experiments versus 351 ppm between the A2WithLUC and B1WithLUC baseline scenarios; Table 4-8). The difference in NEP is even larger among the experiments (Table 4-3) than between the baseline scenarios (Table 4-8) and the variation in land-use emissions among different baseline scenarios. This illustrates the important role of the terrestrial biosphere in the global C cycle.

Table 4-8 Results of different IPCC SRES baseline scenarios

	Atmospheric CO_2		Total CO_2 emissions (Pg $C.yr^{-1}$)		Deforestation emissions (Pg $C.yr^{-1}$)		NEP (Pg $C.yr^{-1}$)		NPP (Pg $C.yr^{-1}$)	
	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100
NoLUC	527	696	20.2	16.0	0.5	0.5	6.4	5.9	77	89
WithLUC	560	749	22.4	17.6	2.7	2.1	6.3	6.6	77	86
A2-NoLuc	491	746	17.0	27.6	0.5	0.5	5.3	7.5	74	91
A2-WithLUC	535	866	18.4	31.0	1.9	3.9	4.3	4.7	75	88
B1-NoLuc	467	514	12.3	5.9	0.5	0.5	4.6	3.2	73	78
B1-WithLUC	485	515	13.2	6.2	1.4	0.8	5.8	4.4	73	77
B2-NoLuc	472	569	12.2	12.1	0.5	0.5	4.7	4.6	73	86
B2-WithLUC	505	602	13.0	12.6	1.2	1.0	4.9	5.0	74	82

4.5 Conclusions

The global and regional consequences of uncertainties in the C cycle were assessed by adjusting the parameterization of ecosystem responses in the IMAGE-2 model to climate and other environmental changes. The analysis was based the use of different assumptions with respect to major biogeochemical processes, as well as the migration ability of species. We also simulated the consequences of combined assumptions in order to evaluate interactions between these processes. Because of the large number of experiments and the regional focus, we were able to evaluate uncertainties more systematically than in many other studies. Furthermore, the integration of the C-cycle model in a large modeling framework has provided the possibility to compare the consequences of uncertainties in the terrestrial response with scenarios of socio-economic and land-use developments.

Although there are large regional differences, a general trend in all experiments has been the simulated increase of the terrestrial C storage in the decades to come. This effectively slows down the increase in atmospheric CO_2. However, the sink function will decrease towards the end of the 21st century and, from our experiments, it cannot be ruled out that this current C sink will turn into a C source. This would imply more stringent mitigation measures to achieve stabilization of GHG concentrations in the atmosphere than anticipated in energy-only models.

The analysis presented has also shown a considerable variation among the experiments in C dynamics. This illustrates the uncertainties involved in predicting the response of the terrestrial biosphere to climate change. The relevance of the different feedback processes depends on the scale considered. Globally, the most important source of uncertainty is the physiological response to increasing CO_2 levels in the atmosphere. Ignoring this effect has larger consequences for the C fluxes and pools than uncertainties in future land use. Developing robust parameterizations for this process should be a key issue in climate change research.

The different consequences of processes other than CO_2 fertilization are of importance, mainly on the regional scale. Different parameterizations for soil respiration are of significance for the C dynamics in the tropics, while in boreal regions the NPP response to temperature determines (together with CO_2 fertilization) mainly the dynamics of C pools and fluxes. The differences with respect to different migration abilities illustrate the need for an enhanced understanding of the spatial dependencies of the response of ecosystems to climate change. This requires the consideration of processes on finer scales: (landscape, for example).

On the basis of the analysis presented, we conclude that the role played by terrestrial biosphere in the global and regional C cycle is complex. This is determined by many interactions and non-linear processes (e.g. based on comparing the individual responses with the combined experiments), which are dynamically and geographically explicit. Some processes are more important than others, depending on the scale. But many of them contribute highly to the apparent uncertainty in the C cycle. Improving the understanding of the biospheric response and reducing some of the shown uncertainties further will improve the robustness of future projections of atmospheric CO_2 concentrations, and offer better control of the extent of mitigation efforts needed to cope with climate change. So far, most of the climate mitigation studies only focus on uncertainties in the energy system, ignoring some of the mechanisms displayed in this analysis.

Chapter 5

The importance of three centuries of climate and land-use change for the global and regional terrestrial carbon cycle [1]

---

[1] This chapter has been published as:

Van Minnen, J.G., K. Klein Goldewijk, E. Stehfest, B. Eickhout, G. van Drecht, & R. Leemans (2008) *Climatic Change,* submitted

Abstract

Large amounts of carbon (C) have been released into the atmosphere over the past centuries. Less than half of this C stays in the atmosphere. The remainder is taken up by the oceans and terrestrial ecosystems. Where does the C come from and where and when does this uptake occur? We address these questions by providing new estimates of global and regional land-use emissions and natural C fluxes for the 1700–2000 period, simultaneously considering multiple anthropogenic (e.g. land and energy demand) and biophysical factors in a geographically explicit manner. The estimates are based on the HYDE dataset of historical land use and a modeling exercise, where natural and land-use (i.e. agriculture, forestry)-related carbon dynamics are integrated with fluxes from energy use and ocean–atmospheric dimensions. This comprehensive approach allows a consistent comparison of the past and present terrestrial fluxes with energy and industrial emissions, both globally and regionally.

The observed historical atmospheric CO_2 concentration profile for the 1700–2000 period is reproduced well in our calculations. The net effect of land-use changes and the terrestrial sink throughout this period was an emission of 35 Pg C towards the atmosphere. If land use had remained constant at its distribution in 1700, then the estimated terrestrial C storage would have increased by 142 Pg C. This overall difference in terrestrial C storage (i.e. 177 Pg C) comes to more than half of the historical fossil fuel-related emissions of 308 Pg C. Globally, historical land-use emissions are dominated by the expansion of cropland and pasture, while timber harvesting only plays a minor role.

Combining the regional land-use and natural C fluxes, North America and Europe were net C sources before 1900, but turned into sinks during the 20th century. Nowadays, these fluxes are a magnitude smaller than energy- & industry-related emissions. Tropical regions were C-neutral prior to 1950, but then accelerated deforestation turned these regions into major C source. The energy- & industry-related emissions are currently increasing in many tropical regions, but are still smaller than the land-use emissions.

Based on the presented relevance of the land-use and natural C fluxes for the historical C cycle and the significance of fossil fuel emissions nowadays, there is a need for an integrated approach for energy, nature and land use in evaluating possible climate change mitigation policies.

5. The importance of three centuries of climate and land-use change for the global and regional terrestrial carbon cycle

5.1 Introduction

The increasing atmospheric carbon dioxide (CO_2) concentration – from its pre-industrial level of 280 parts per million (ppm) to the current level of 380 ppm – has led to a warmer climate (Hegerl *et al.*, 2007). Although fossil fuel emissions dominate this CO_2 increase, land use also played a substantial role (Denman *et al.*, 2007). Land-use conversions, such as deforestation and agricultural expansion, have contributed considerably to the cumulative atmospheric CO_2 increase (see for example, Achard *et al.*, 2002; Houghton, 2003). At the same time, natural vegetation, forest plantations and other land covers sequester C, resulting in a slowing down of the atmospheric CO_2 increase.

The role of the energy sector is dominant in the literature on increasing CO_2 concentrations, resulting in consistent estimates of historical energy emissions (e.g. Marland & Boden, 2000). In contrast, there are large uncertainties in the estimates of historical land-use emissions and the natural C sink. With respect to land use, historical changes are, first of all, difficult to assess, given the lack of data in many regions. To date, only two accepted global land-use datasets have been compiled (Ramankutty & Foley, 1998; Klein Goldewijk, 2001). Second, the processes underlying historical land-use change are diverse and hard to track. For example, deforestation for timber use has a very different impact on the carbon (C) cycle than deforestation for agricultural expansion. Third, different methodologies have been used in estimating the historical land-use emissions. Houghton (2003), Fearnside (2000) and Ramankutty *et al.* (2007), for example, used book-keeping methods with fixed C densities to estimate historical land-use emissions, ignoring feedback mechanisms between atmospheric CO_2, climate and terrestrial C dynamics. This approach leads to overestimates, since compensating responses by the terrestrial system are ignored. Achard *et al.* (2002) and DeFries *et al.* (2002) applied remote sensing techniques, showing smaller deforestation areas and consequently lower land-use emissions. Finally, also the model type used, the choice of processes included with assumptions made are important for the outcome. With respect to the processes, McGuire *et al.* (2001), for example, excluded the harvesting of timber and therefore turned up a relatively low historical deforestation in the 20th century.

The consequences of these uncertainties can be illustrated by the broad range of land-use emissions that is available, even for the last few decades. For example, the estimated global emissions for the 1980s vary from 0.6 (DeFries *et al.*, 2002) to 2.4 Pg C yr^{-1} (Fearnside, 2000)[2]. Likewise, the range for the 1990s goes from 0.6 Pg C yr^{-1} (Achard *et al.*, 2002) to 2.2 Pg C yr^{-1} (Houghton, 2003).

With respect to the historical natural sink, the variation in the C cycle per ecosystem type contributes to the uncertainty in terrestrial C fluxes. Furthermore, the variation in terrestrial C fluxes can be explained by the numerous ecological processes involved that change over time and space, and thus result in different sink estimates (Zaehle *et al.*, 2005; Stephens *et al.*, 2007).

The number of uncertainties, as mentioned above, have led to the recommendation by Ramankutty *et al.* (2007) to develop more coherent and consistent land-use emission estimates using three criteria: (1) consider the full land-cover dynamics during and following deforestation (including effect on soil carbon); (2) consider explicitly historical land-use changes, and (3) accurately estimate the fate of cleared carbon. Only a methodology applying these three criteria is believed to deliver “realistic” estimates of the role of historical land-use change in the global carbon cycle.

In this paper, we propose a methodology that allows for analyses over a period of 300 years, explicitly taking into account historical land-use change and the complete life cycle of cleared carbon. Moreover, we use a terrestrial C cycle model (Klein Goldewijk et al., 1994) that considers land-use dynamics after deforestation (including re-growth of natural vegetation, Van Minnen *et al.*, 2000). The model also includes many feedbacks between atmosphere and the terrestrial system (Leemans *et al.*, 2002). By using this C cycle model in a geographically explicit manner and applying it to the historical land-use data set HYDE (Klein Goldewijk, 2001), we establish a consistent experimental set-up that meets the criteria, as defined by Ramankutty *et al.* (2007). Moreover, the geographical explicitness of this approach enables a regional comparison of the major C fluxes.

In section 2, the methodology of this approach will be explained in further detail. Results and a discussion of these results are given in section 3. Finally, section 4 draws conclusions from this methodology.

---

[2] Note that studies such as DeFries et al. (2002) and Fearnside (2000) provide emissions for tropical regions, assuming negligible emissions in the remainder of the world.

5.2 Methodology

In order to assess the C cycle over the past three centuries, the integrated assessment model IMAGE 2 (Integrated Model to Assess the Global Environment; MNP, 2006) has been coupled to the HYDE database (History Database of the Global Environment; Klein Goldewijk, 2005; Klein Goldewijk *et al.*, 2007), which includes land-use information for cropland and pasture. Land-use information for timber was estimated internally in IMAGE 2. Various parts of IMAGE 2 were by-passed and replaced by external input. This external information deals with the historical land use for cropland and pasture (from HYDE, see next section), historically energy-related greenhouse gas emissions, and climate (see section on model set-up).

5.2.1 Historical land-use change

Figure 5-1 depicts the estimated development of agricultural and pasture land worldwide over the past three centuries at four moments in time, as developed by HYDE. HYDE is a database of historical time series for the period of 1700–2000, and includes land-use information on cropland and pasture (Klein Goldewijk, 2001; Klein Goldewijk *et al.*, 2007). For 1700 an area of about 2.6 Mkm^2 cropland and about 2.8 Mkm^2 pasture has been estimated, mainly in India, eastern China and Europe. The area is considerably less than the estimates of Houghton *et al.* (1983). This difference is due, for example, to the fact that Houghton *et al.* (1983) estimated 0.24 Mkm^2 pasture in Oceania in 1700, which seems very high since the first settlers arrived in Australia and New Zealand only at the end of the 18th century. For the early 19th century it is estimated that large parts of Russia and of theAfrican coastal areas became colonized. Agriculture in the USA, southern America and India rapidly developed in the second half of the 19th century. Vast land-use changes in tropical regions started early in the 20th century. Over the last half century, some parts of the agricultural land in the USA, Europe and Asia were abandoned, resulting in new forests and natural grasslands. Globally, HYDE estimates that there is now about 15 Mkm^2 of cropland around the world and 16 Mkm^2 of grassland pasture (compared to 34 Mkm^2 of total grassland, based on FAO information).

The HYDE data for the period of 1961–2000 are based on FAO statistics for “Arable land and Permanent Crops” (FAO, 2006). Permanent pasture estimates have been based on the use of “real” grassland areas, as defined by satellite-based maps (Loveland *et al.*, 2000; Bartholome *et al.*, 2002). We haven’t used FAO data for permanent pasture because overlay analysis with these remote sensing datasets showed large areas of the Permanent Pasture category of the FAO to be more or less natural land-cover types (such as savanna). This resulted in a much lower extent of pasture areas over the last decades than the FAO estimates (i.e. globally, 46% lower in the year 2000).

For the pre-1960 period several additional data sources were used for allocating land in the pre-1960 period, (Klein Goldewijk *et al.*, 2007). Globally, the comprehensive historical statistics of Mitchell (1993;1998a,b) and Richards (1990) were used, while regional information from Richards & Flint (1994) is used for Asia, and information from Houghton (1991, 2003) for historical land use in Latin America.

Because historical land-use information is rarely geographically explicit, four assumptions have been used in HYDE for allocating the historical information over the geographical 0.5° by 0.5 ° grid. Firstly, coastal areas and river plains with fertile soils are most favorable for early settlement. Secondly, historical (rural) population densities and agricultural activity are strongly correlated. For this reason, historical population density maps (also part of HYDE) are used as a proxy for the land-use allocation. Thirdly, historical agricultural activity first starts near freshwater resources (rivers and lakes). Fourthly, old growth forests are less prone to conversion to agriculture than other land-cover types (Klein Goldewijk *et al.*, 2007). All of these assumptions were transformed into single weighting maps for cropland and pasture for each historical time step, for which the allocation of the statistics was carried out (Figure 5-1).

In addition to land-use changes for cropland and pasture, we also deal in this study with the consequences of timber harvest for the C cycle. For this purpose, the timber demand for all IMAGE-2 regions was estimated on the basis of a linear increase between 1700 (no demand) and 1970, followed by the FAO statistical information up to 2000.

5.2.2 Natural vegetation

After allocation of arable land and pastureland, the other areas are covered by one out of 14 natural ecosystems or biomes. The distribution of these biomes is computed by using the BIOME model in IMAGE 2 (Leemans & van den Born, 1994). BIOME is a static biogeographical model that uses the external climate information (i.e. temperature, precipitation, cloudiness) and internally computed atmospheric CO_2 concentration to estimate the (equilibrium) biome distribution worldwide. Vegetation dynamics are introduced in IMAGE 2 by transition rules to mimic different migration and establishment capabilities of species (Van Minnen *et al.*, 2000). We assume, for example that the conversion from tundra into boreal forest occurs more rapidly than the conversion from one forest type to another.

The combination of HYDE and the natural vegetation model of IMAGE 2 provided the estimated land-use and land-cover patterns for the period of 1700–2000. These patterns were updated every five years, allowing for four land-use transitions: (i) natural vegetation changes towards cropland or pasture; (ii) forest change to "re-growth forests" due to timber harvest; (iii) agricultural land converting back to natural vegetation cover because of land abandonment and (iv) conversions from one type of natural vegetation towards another due to climate change.

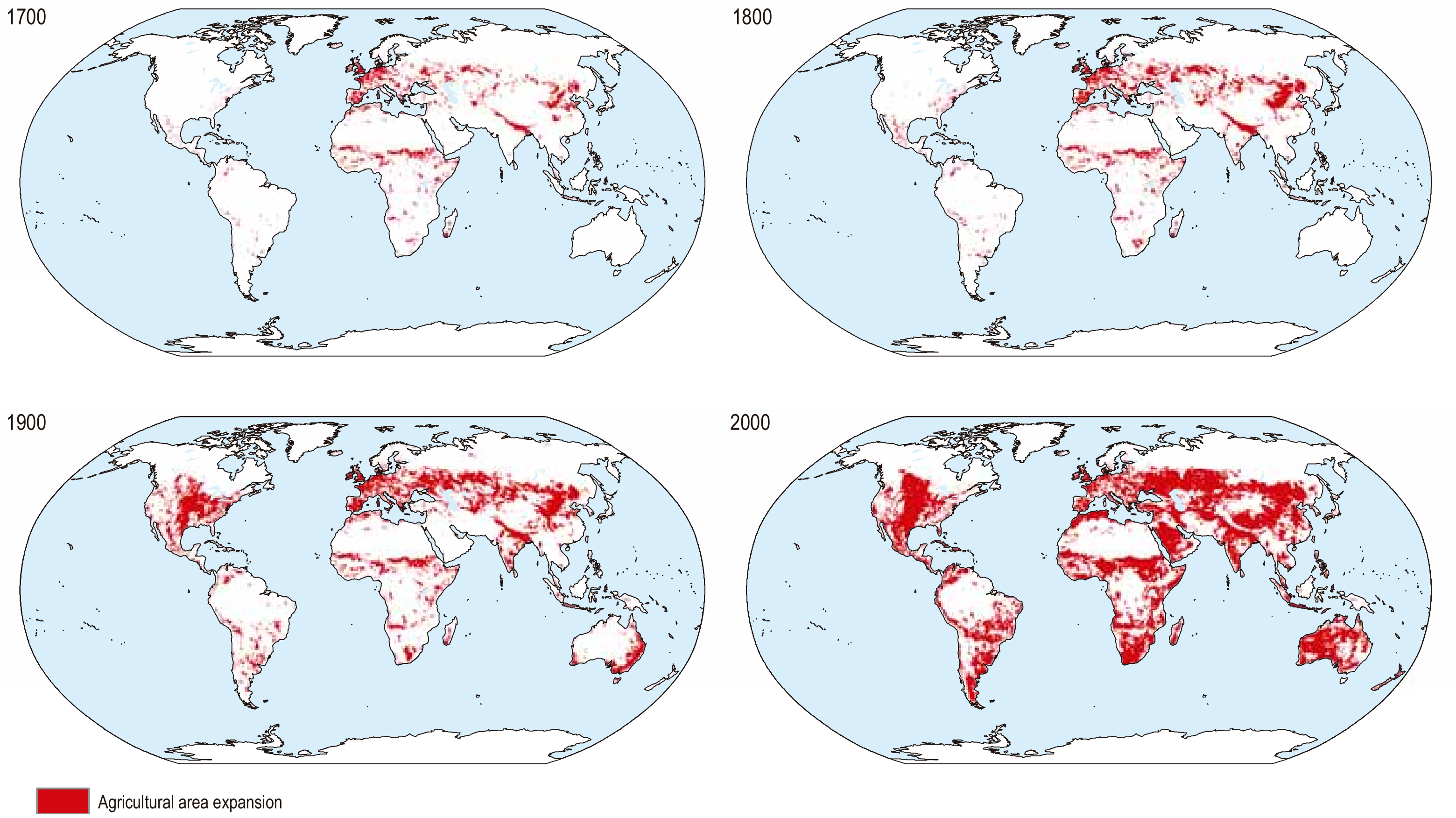


Figure 5-1 Reconstructed agricultural area in various years from 1700 to 2000.

5.2.3 Consequences for the C cycle

The main objective of this study is to assess the role of land-use change and natural ecosystems in the historical C cycle. The historical atmospheric CO_2 concentration is estimated by taking into consideration: (i) the biosphere[3]–atmosphere and ocean–atmosphere C exchange, and (ii) the historical energy and industry-related emissions. The ocean–atmosphere C exchange is computed using the ocean model of IMAGE 2, taking into account temperature and atmospheric CO_2 concentration. The C exchange between the biosphere and atmosphere is computed with the terrestrial C-cycle model of IMAGE 2 (Klein Goldewijk *et al.*, 1994;Van Minnen *et al.*, 2000; Van Minnen *et al.*, 2006), using changes in land cover, climate, and atmospheric CO_2. This model is described here in more detail, because of its relevance for the objectives of this paper.

The driving force of the IMAGE-2 C-cycle model is Net Primary Productivity (NPP), i.e. the photosynthetically fixed C minus C losses due to plant respiration. NPP is a function of atmospheric CO_2, climate, soil nutrient and moisture status, biome type, and the development stage of a biome. The next important process is the Net Ecosystem Production (NEP), which is the net C flux between the atmosphere and terrestrial ecosystems (often called residual sink). NEP is calculated as NPP minus the C losses due to heterotrophic soil respiration. Soil respiration depends on the C stocks in three different soil compartments (i.e. litter, humus, and charcoal), their turnover rates, and environmental conditions (i.e. soil water availability and temperature). All fluxes are calculated on a monthly time step, whereas the carbon pools are updated annually.

The IMAGE-2 terrestrial C-cycle model deals explicitly with the four land-cover transitions as described above. During a conversion towards agricultural land, the C pools in leaves and roots are transferred as slash and dead organic matter to the soil humus pools. In the case of tropical regions, stems and branches partly enter the soil pool and partly disappear into the atmosphere (mimicking burning). For the other regions, it is assumed that the woody biomass is used to satisfy the regional and global wood demand. During the land-cover conversion towards “re-growth forest”, the C pools are initially reduced due to timber harvest and followed by re-growth. After a certain period these “re-growth forests” return back to one of the main forest types, and can then potentially be used again. Leaves and roots enter the soil C pools again, stems are either stored as pulpwood and particles (with a turnover rate of 10 years), or veneer, and saw logs (with turnover rates of 100 years). The natural conversions alter the C dynamics in way that the C characteristics slowly convert from the old to the new biome using conversion-specific transient periods (Van Minnen *et al.*, 2000).

---

[3] We define the biosphere as that part of the terrestrial earth within which life occurs, and in which biotic processes, in turn, alter or transform (http://nl.wikipedia.org/wiki/Biosfeer)

5.3 Model set-up and experimental design

For the historical analysis presented here, various parts of IMAGE 2 were by-passed and replaced by external input for the period of 1700–2000 (Figure 5-2). Furthermore, an additional growth factor is added to the terrestrial C-cycle model.

This external information deals with the historical land use for cropland and pasture (from HYDE), historical energy-related greenhouse gas emissions, and climate. The energy-related emissions are taken from Marland & Boden (2000), who presented emissions per country for the period of 1751–2000. The emissions were hind-casted back to 1700 by computing the per capita emissions in 1751, and multiplying them with the population figures provided by HYDE for the period 1700–1750, assuming constant per capita emissions. The climate information (i.e. monthly temperature and precipitation) for the period of 1900–2000 was taken directly from New *et al.* (2000), using decadal means. For the climate before 1900 we simply assumed a constant climate based on the 1900–1930 average of New *et al.* (2000), because of the limited variation in the long-term pre-industrial climate (Levy *et al.*, 2004).

With respect to the terrestrial C-cycle model, we added an autonomous factor – affecting the NPP in a grid cell – to account for historical non-climate growth stimuli. Various studies (e.g. Kaipainen *et al.*, 2004; Milne & van Oijen, 2005; De Vries *et al.*, 2006) have suggested that N deposition and management changes have been very relevant for the growth increase, as observed during the 20th century in various ecosystems in mid-latitudes. This information has been adopted here by considering a 10–40% NPP increase during the 20th century for boreal, cool, and temperate forest types and a 13% increase for agriculture.

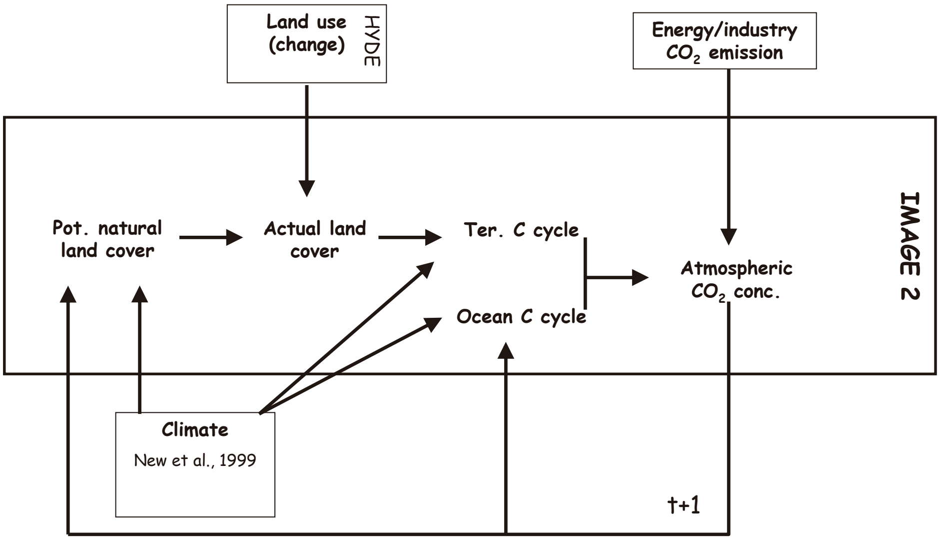


Figure 5-2 Steps for assessing the historical global C cycle.

In order to assess the role of land-use change and natural ecosystems in the historical global C cycle, we included four experiments with different land-use change assumptions (Table 5-1). Next to the standard set-up described above ("baseline"), we included an experiment in which cropland and pasture were kept constant in their 1700 pattern, and timber harvest was excluded ("NoLUC"). This experiment shows the overall relevance of land use across different world regions. In the third experiment, alternative historical land-use patterns for pasture based on statistical FAO information for the last three decades were used (FAO). This experiment has been included because of the broad range of data for the historical pasture areas. Finally, we kept cropland and pasture constant for the 1700 pattern, but included land use for timber ("OnlyWood").

Table 5-1 Overview of experiments included

Experiment	Description
Baseline	1700–2000 experiment using FAO statistics and satellite information in HYDE for historical cropland and pasture, respectively. Historical land-use change for timber is estimated internally in IMAGE 2.
NoLUC	1700–2000 experiment with no historical land-use changes, either for cropland, pasture, or timber (i.e. the 1700 land-use pattern is used for entire period.)
OnlyWood	1700–2000 experiment considering only land-use emissions from wood harvest. Crop and pasture use is kept constant, adhering to the 1700 pattern.
FAOinfo	1700–2000 experiment using only FAO statistical information in HYDE for both historical cropland and pasture. Historical land-use change for timber is estimated internally in IMAGE 2

5.4 Results & discussion

5.4.1 Global analysis

Figure 5-3 depicts the simulated CO_2 concentrations for the period of 1700–2000 and Figure 5-4, Figure 5-5 and Table 5-2 all show different aspects of the relevant C fluxes. The land-use flux over the last three centuries is 140 Pg C, which, along with the energy-related emissions (308 Pg C, (Marland & Boden, 2000), amounts to total emissions of 448 Pg C. Due to the uptake by oceans and the terrestrial ecosystems, only 44% of these emissions are estimated to have remained in the atmosphere, resulting in a 92 ppm increase in atmospheric CO_2 concentration (Figure 5-3). This is well in line with the Mauna Loa record (Keeling & Whorf, 2001).

Despite a considerable uptake of 106 Pg C of the natural ecosystems (i.e. the resulting NEP), the terrestrial biosphere is estimated to emit 35 Pg C over the period of 1700–2000. This is due to the 140 Pg C emissions from the expansion of cropland and pasture, and from timber harvest (Table 5-2, Figure 5-4). After 1950 the biosphere turned into a net C sink (Figure 5-5). Land-use emissions were found to increase, especially beyond 1850. Two main increases in land-use emissions due to

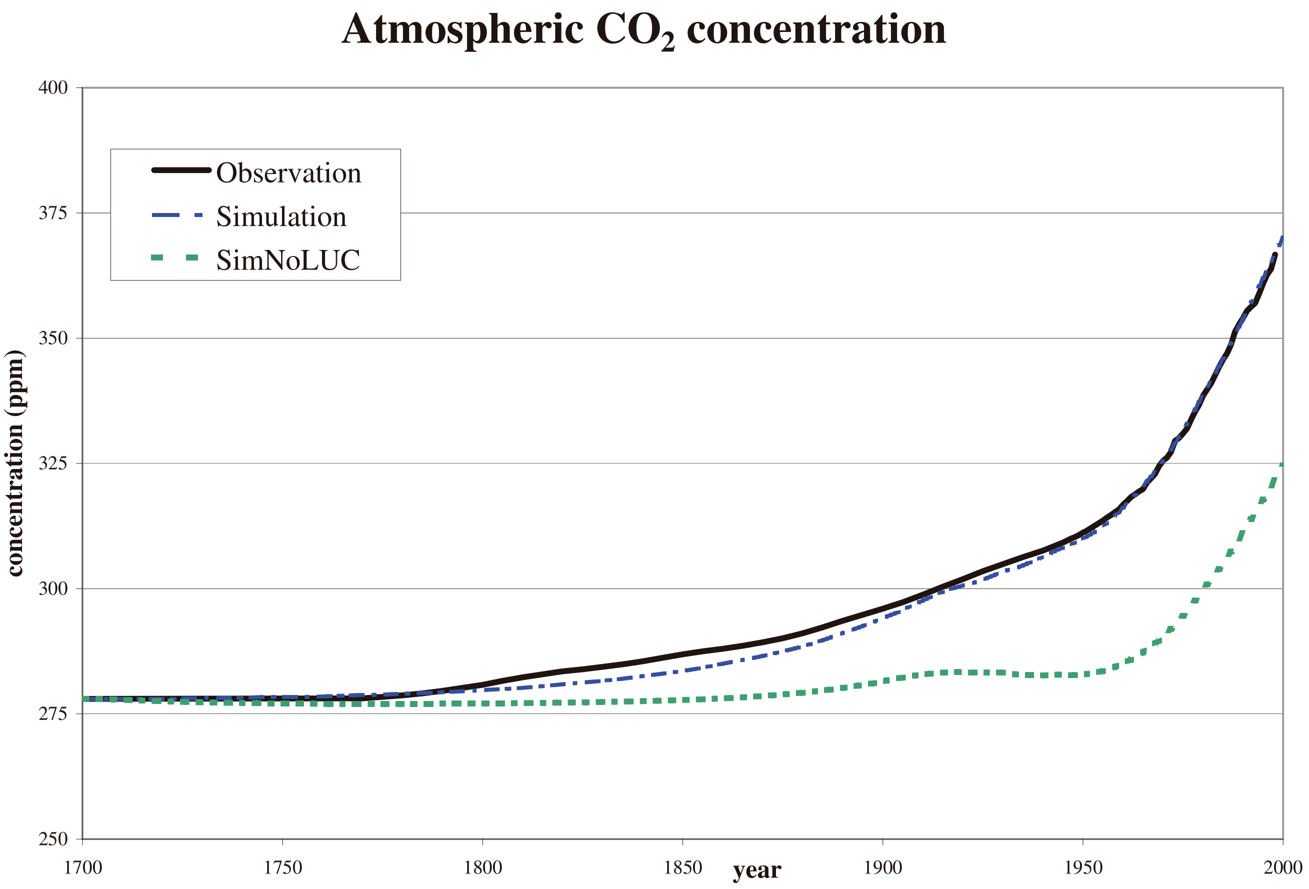


Figure 5-3 Historical simulated CO_2 profile compared to observations (Mann, 2002).

considerable land-cover conversions were computed, first in mid-latitudes (around 1900) and then in tropical regions (after 1950). After 1970 the total estimated land-use emissions decreased again to 1.3 Pg C yr^{1} (during the 1980s and 1990s).

The estimated land-use emissions are considerably lower than in Houghton (2003) (Table 5-2). Firstly, the difference is both the result of different deforestation estimates and the consideration of afforestation. Although it is too early to state that Houghton (2003) had overestimated historical deforestation (Denman *et al.*, 2007), the rates are 30–60% higher than in most other studies. The high deforestation rates, based on national reports/statistics, were often compiled without checking consistency between countries (see also Denman *et al.*, 2007; Ramankutty *et al.*, 2007). Secondly, Houghton (2003) used fixed C densities for different land-cover categories, whereas these vary in time and space due to climate variation, different stages of the ecosystem (i.e. young versus old), and different environmental conditions. Our estimated land-use emissions for the 1980s and 1990s are slightly higher than values given by McGuire *et al.* (2001) and Achard *et al.* (2002). This might be caused by the explicit consideration of the long-term land-cover changes in our analysis. Ramankutty *et al.* (2007) identified this as one of the critical issues for an accurate estimation of the historical land-use emission. Furthermore, we have included land-use emissions associated with forestry activities. These emissions are substantial in mid- and high-latitude regions. Many studies, including McGuire *et al.* (2001) and Achard *et al.* (2002) have, however, ignored these emissions.

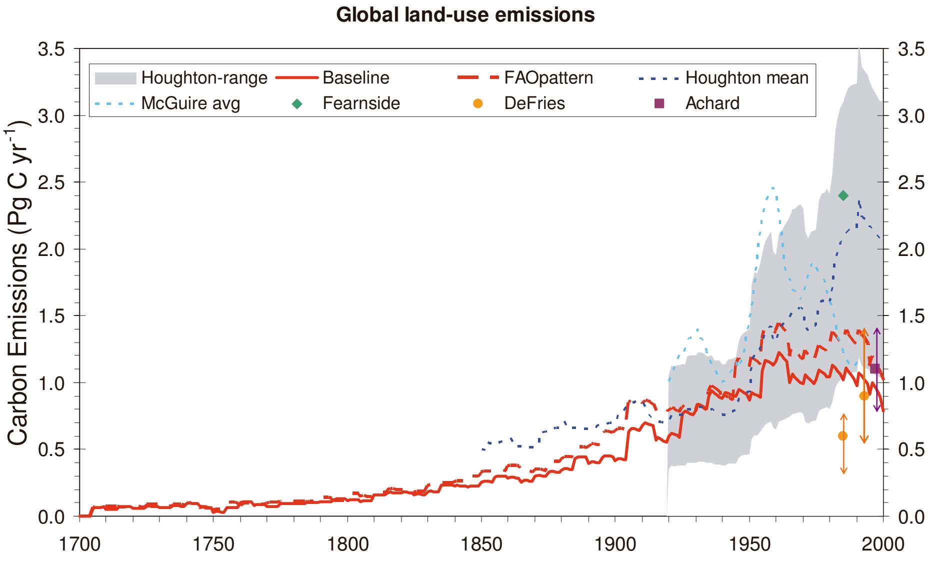


Figure 5-4 **Historical simulated CO_2 emissions from land use, compared to other sources. Note that two lines represent model results using alternative land-use patterns. Other data sources derived from Ramankutty *et al.*, 2007. Data sources are: Fearnside, 2001; McGuire *et al.*, 2001; Achard *et al.*, 2002; DeFries *et al.*, 2002; Houghton, 2003).**

Table 5-2 Global C budget

a) Baseline results in comparison with the literature

	1700–2000 (Pg C)		1850–2000 (Pg C)			1980s (Pg.C. yr^{-1})					1990s (Pg.C. yr^{-1})				
	Base	Ref6	Base	Ref1	Ref6	Base	Ref1,5	Ref2,4	Ref 7	Ref8	Base	Ref1	Ref3,4	Ref 7	Ref8
Atmos. increase	197		185			3.2	3.3			3.3±0.1	3.4	3.2			3.2±0.2
Energy emis.[4]	308		299			5.6	5.4			5.4±0.3	6.4	6.3			6.4±0.4
Ocean–Atmos.	-146		-127			-1.9	-1.7		-1.8±0.8	-1.8±0.8	-2.2	-2.4		-2.1±0.7	-2.2±0.4
Land–Atmos.	35	97	13		51	-0.5	-0.4		-0.3±0.9	-0.3±0.9	-0.8	-0.7		-1.0±0.8	-1.0±0.6
LUC emis..	140	222	123	150	172	1.3	2.0–2.4	0.6– 0.8	0.9 – 2.8	1.4±1.0	1.3	2.2	0.9–1.1	1.4–3.0	1.6±1.1
Res. ter. sink	-106	-125	-110		-121	-1.8	-2.4		-4.0 to -0.3	-1.7±1.5	-2.1	-2.9		-4.8 to -1.6	-2.6±1.7

References: Ref1 – Houghton, 2003; Ref2: McGuire *et al.*, 2001; Ref3: Achard *et al.*, 2002; Ref4: DeFries *et al.*, 2002; Ref5: Fearnside, 2000; Ref6: Levy *et al.*, 2004; Ref 7: House *et al.*, 2003; Ref8:Denman *et al.*, 2007, based on averaging Houghton and DeFries *et al.*, 2002.

b) Alternative land-use assumptions: No changes at all (“NoLUC”); land-use changes, but only for timber (“Only wood”)

	1700–2000 (Pg C)			1850–2000 (Pg C)			1980s (Pg.C. yr^{-1})			1990s (Pg.C. yr^{-1})		
	FAO	NoLUC	Only wood	FAO	NoLUC	Only wood	FAO	NoLUC	Only Wood	FAO	NoLUC	Only Wood
Atmos. increase	204	100	103	191	100	103	3.3	2.5	2.5	3.5	2.8	2.9
Emissions[4]	308	308	308	299	299	299	5.6	5.6	5.6	6.4	6.4	6.4
Ocean – Atmos.	-153	-66	-70	-134	-57	-60	-3.3	-1.1	-1.2	-3.5	-1.5	-1.5
Land – Atmos.	49	-142	-135	26	-142	-136	-0.4	-2.0	-1.9	-0.7	-2.1	-2.0
LUC emis.	167	0	44	147	0	38	1.6	0	0.4	1.6	0	0.5
Res.ter. sink	-117	-142	-180	-121	-142	-174	-2.0	-2.0	-2.4	-2.3	-2.1	-2.5

---

[4] Derived from Marland & Boden (2000)

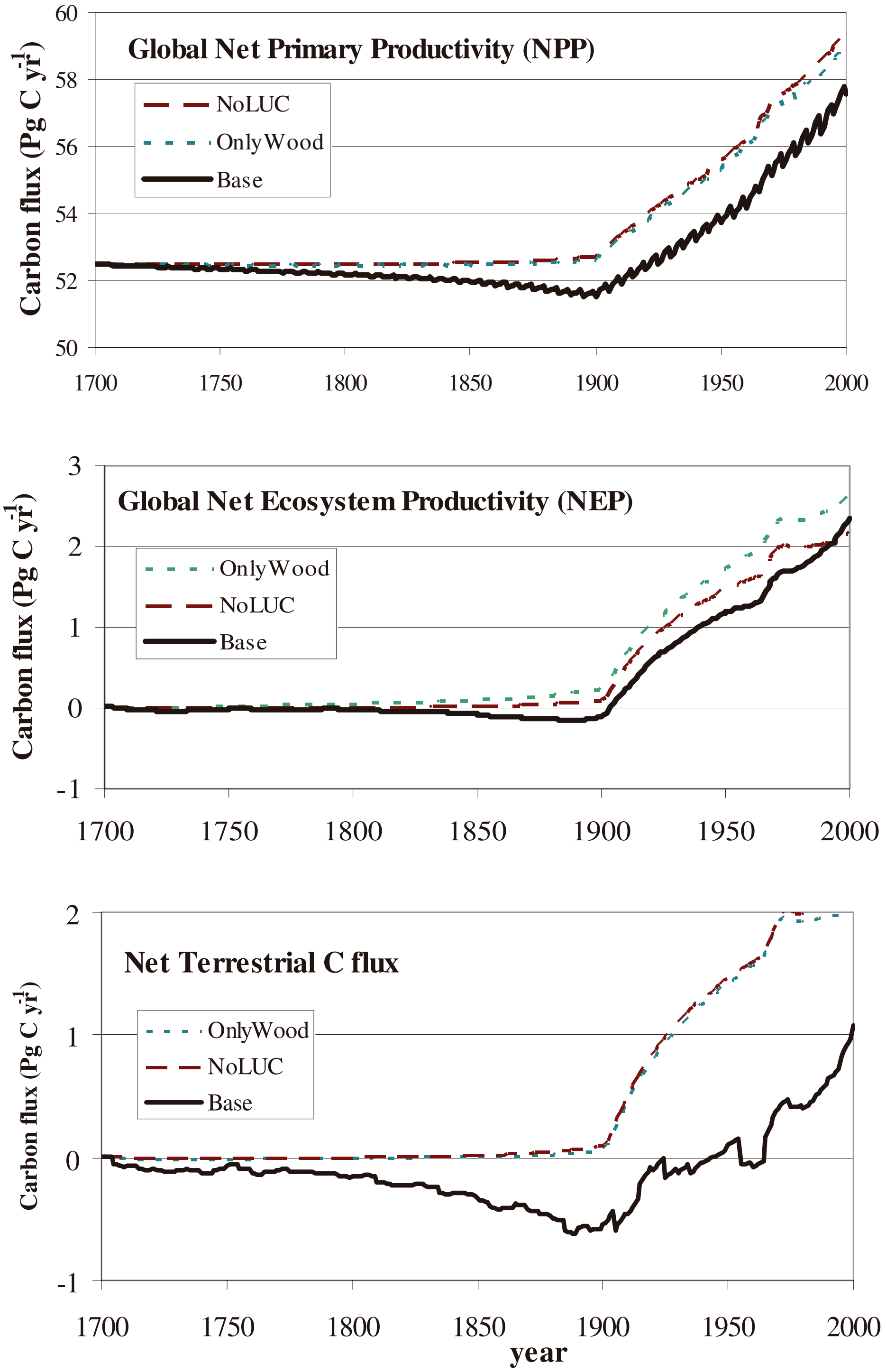


Figure 5-5 Global C fluxes (Pg C yr^{-1}) over the historical period with different assumptions on land-use change (note that a positive value implies a terrestrial uptake).

When changes in land use were not considered, either for cropland, pasture, or timber, the C storage in the biosphere was estimated to increase by 142 Pg C during 1700 to 2000, instead of decreasing by 35 Pg C (Table 5-2b). This difference of 177 Pg C is little more than half the historical fossil fuel-related emissions of 308 Pg C for the period of 1700–2000, illustrating the significant contribution of historical land-use changes to the observed increase in atmospheric CO_2. Excluding land-use changes results in a considerably lower CO_2 profile, ending with a concentration of 325 ppm in 2000 (Figure 5-3). Direct land-use emissions are responsible for 80% of this difference, while 20% is caused by a reduced uptake of natural ecosystems (e.g. less C stored in wood and soil) (Figure 5-5). Note that without land-use changes, the ocean uptake is reduced about 50% (Table 5-2) due to the lower CO_2 concentration in the atmosphere. Without this feedback, the atmospheric CO_2 concentration profile would be even lower.

A comparison of the different causes of changes in land use shows a dominant role on the global level for cropland and pasture, compared to timber (Table 5-2b). Allowing only wood harvest, and keeping cropland and pasture constant at its 1700 pattern, results in a land-use flux of 44 Pg over the past three centuries. These emissions are, however, almost compensated by an increased biospheric uptake, which is the result of more young re-growing forests. In total, the CO_2 concentration profile is comparable to the profile excluding any land-use changes (Figure 5-3).

The overall biospheric C uptake or residual sink (i.e. NEP) is estimated to be 106 Pg C over the period 1700–2000 (Table 5-2). If we exclude land-use changes, the uptake comes to 142 Pg C. The largest terrestrial uptake is found to occur in the 20th century (Figure 5-5). Until 1900 the estimated global NEP and underlying NPP fluxes slightly decreased due to the changes in land use. During the 20th century, the global NPP flux increased from about 52 Pg C yr^{-1} up to 58 Pg C yr^{-1} in 2000. These NPP values fit well with the ranges of a model inter-comparison (44–66 Pg C yr^{-1}, Cramer *et al.*, 2001) and with those synthesized recently by the IPCC (54–63 Pg C yr^{-1}, Fischlin *et al.*, 2007). The estimated NEP flux is found to increase from about zero around 1900 up to 1.8 and 2.1 Pg C yr^{-1} averaged over the 1980s and 1990s, respectively (Table 5-2). This estimated sink increase is the result of a combination of climate, CO_2 fertilization, land use (e.g. abandoned agricultural land in the early 20th century, resulting in new forests, Figure 5-5), and the autonomous growth factor, accounting for nitrogen fertilization and management changes in mid- and high-latitudinal forests. This corresponds with the literature, suggesting that climate (Churkina *et al.*, 2005) and atmospheric CO_2 (Nemani *et al.*, 2003; Novak *et al.*, 2004), changes in ecosystem management (Kaipainen *et al.*, 2004; Phat *et al.*, 2004) and nitrogen fertilization (Milne & van Oijen , 2005; De Vries *et al.*, 2006) are the main drivers of the observed biospheric C uptake. Note that the CO_2 fertilization effect on the terrestrial uptake is larger in the baseline than when we exclude land-use changes; this is because the latter results in 65 ppm lower atmospheric CO_2 concentration in 2000 (Figure 5-3).

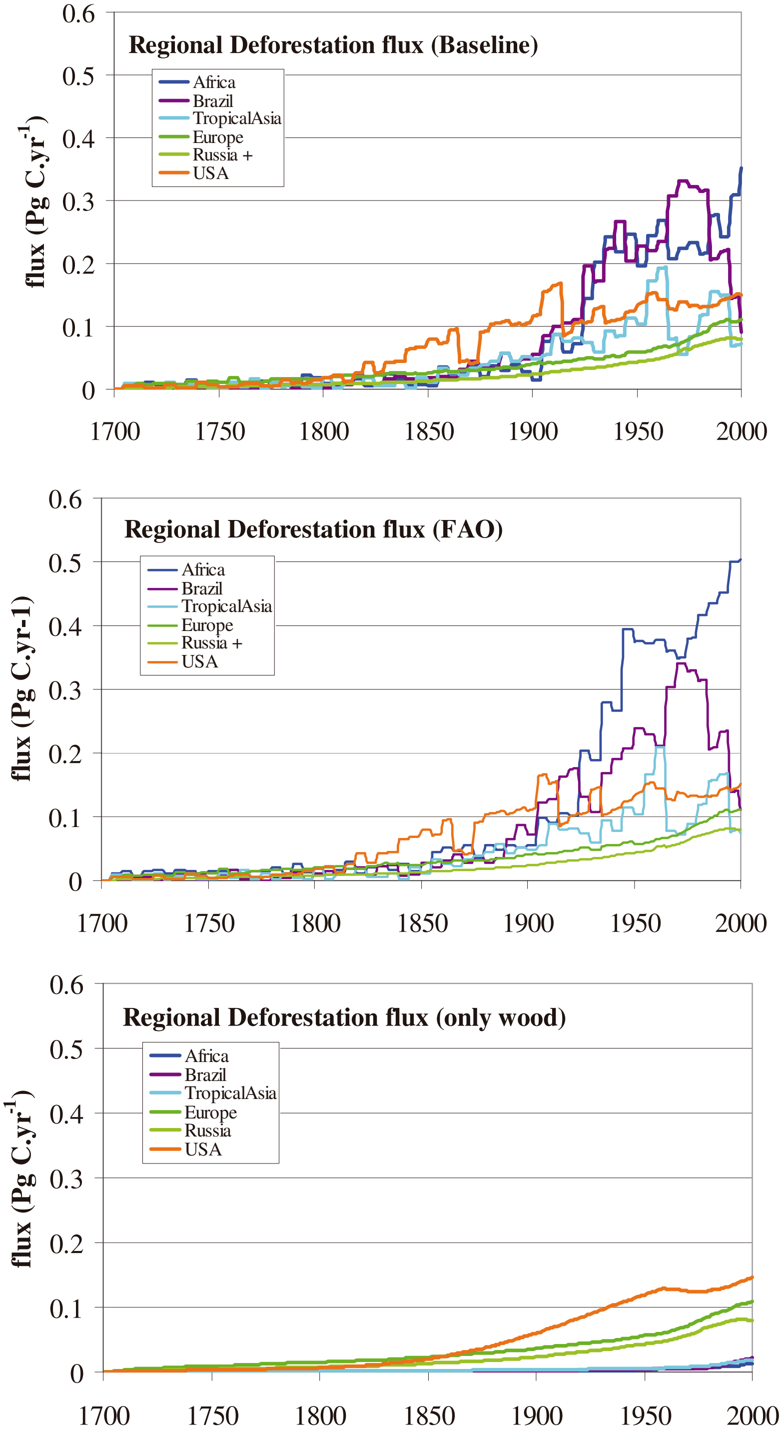


Figure 5-6 Regional land-use change for C emissions (Pg C yr^{-1}). The top panel includes land-use changes based on the baseline land-use pattern; middle, all the land-use changes based on the FAO land-use pattern, and bottom, only land-use changes for wood harvest.

Table 5-3 Regional fossil fuel and terrestrial C fluxes at different times over the past three centuries (in Pg C yr^{-1}), where a positive number represents emissions into the atmosphere

a) Land-use emissions

Region	Average 1700–1800	Average 1800–1850	Average 1850–1900	Average 1900–1950	1980s	1990s
Europe	0.02	0.02	0.03	0.05	0.10	0.11
Russia	0.01	0.01	0.02	0.03	0.07	0.08
USA	0.04	0.04	0.08	0.12	0.13	0.15
China	0.0	0.0	0.01	0.02	0.07	0.09
South America	0.03	0.03	0.08	0.25	0.41	0.32
Tropical Asia	0.01	0.01	0.04	0.08	0.14	0.11
Africa	0.01	0.01	0.03	0.14	0.25	0.28

b) Net land–atmosphere flux

Region	Average 1700–1800	Average 1800–1850	Average 1850–1900	Average 1900–1950	1980s	1990s
Europe	0.02	0.04	0.04	-0.04	-0.13	-0.13
Russia	0.0	0.01	0.01	-0.16	-0.33	-0.34
USA	0.01	0.08	0.24	0.12	-0.21	-0.22
China	0.0	0.0	0.0	-0.08	-0.13	-0.11
South America	0.01	0.03	0.07	0.24	0.51	0.28
Tropical Asia	0.01	0.01	0.04	0.08	0.10	0.07
Africa	0.01	0.0	0.0	0.07	0.09	0.03

c) Fossil fuel emissions[5]

Region	Average 1700–1800	Average 1800–1850	Average 1850–1900	Average 1900–1950	1980s	1990s
Europe	0.0	0.02	0.15	0.40	1.21	1.15
Russia	0.0	0.0	0.0	0.04	0.64	0.48
USA	0.0	0.0	0.06	0.43	1.23	1.41
China	0.0	0.0	0.0	0.01	0.55	0.85
South America	0.0	0.0	0.0	0.01	0.14	0.19
Tropical Asia	0.0	0.0	0.0	0.0	0.08	0.17
Africa	0.0	0.0	0.0	0.01	0.16	0.20

---

[5] Derived from Marland & Boden (2000)

5.4.2 Regional assessment

Here we provide regional explicit information on land use and natural C fluxes for the period of 1700–2000. Only few studies have provided such information (Houghton, 2003; House *et al.*, 2003; Ramankutty *et al.*, 2007). However, these studies have in general various disadvantages with respect to the limited time period, approach used (seldom integrated), and spatial focus. Nevertheless, we will use these sources for comparison wherever possible.

Large regional differences were found for the natural C fluxes and land-use emissions over the past three centuries (Figure 5-6a, Table 5-3). Concerning land-use emissions, Europe and especially North America showed high emissions by the end of the 19th century, whereas tropical regions – especially South America – became C emitters mainly in the 20th century. The land-use emissions form the most relevant contribution of tropical areas — especially Africa and South America — to the increase in atmospheric CO_2. Although energy & industry-related emissions are increasing in some of these regions, these are still relatively low in most countries where land-use changes occur (Table 5-3).

The estimated land-use emissions in most regions across the world have stabilized or even decreased over the past decades. The land-use emissions in the USA, for example, peaked around 1900 (0.17 Pg $C.yr^{1}$) and dropped down to about 0.13–0.15 Pg C for the 1980s and 1990s, well within the range of figures provided by Houghton (2003) (i.e. 0.12 ± 0.2 Pg C). Likewise, the land-use emissions in Brazil (and other parts of South America) peaked in the 1980s, followed by a considerable decrease. Note that the estimated emissions for South America are substantially lower than in Houghton (2003) — possibly due to his high deforestation rates (Denman *et al.*, 2007; Ramankutty *et al.*, 2007) — but in line with House *et al.* (2003). Exceptions for the stabilizing or decreasing land-use emission trends are Africa and China, where large-scale land-use changes continue to occur, resulting in increasing emissions (Figure 5-6, Table 5-3).

In most tropical regions, the estimated land-use emissions have been caused mainly by land conversions for additional crop and pasture land. Timber played a more important role in many temperate regions of North America, Europe, and Russia. The increasing wood demand in these regions has resulted in direct land-use emissions that have counterbalanced the decreased emissions from agricultural and pasture caused by increasing abandonment of agricultural land (Figure 5-6b, Table 5-3).

Using the FAO land-use information for historical pasture instead of satellite-based information has resulted in significant higher land-use emissions, especially in tropical regions (Figure 5-6b). In Africa, for example, the emissions in 2000 were found to be 42% higher due to the larger deforestation rates. For many temperate regions the effect was small because of the larger robustness of the assumed land-use changes (Klein Goldewijk *et al.*, 2007). The substantial effect of different assumptions related to historical land-use changes on the terrestrial C balance shows that an accurate land-use pattern is essential for getting more robust land-use emissions, especially in tropical regions. This supports the findings of Hurtt *et al.* (2006) and Ramankutty *et al.* (2007).

The estimated C fluxes of natural ecosystems have also shown a considerable regional variation (Table 5-3a,b). Although the highest NPP rates were found for tropical regions, the largest NPP increase and terrestrial C sink were found for mid- and high-latitude ecosystems. Up to 1900, most ecosystems around the world are estimated to have been approximately carbon neutral. The uptake rates in Europe, Russia and the USA increased up to 0.24, 0.42 and 0.37 Pg C yr^{-1}, respectively, in the 1990s (comparing Table 5-3a and Table 5-3b). This increase was less in tropical regions, sometimes significantly, down to only 0.04 Pg C yr^{-1} in tropical Asia and South America. This spatial differentiation is caused by the fact that all aforementioned factors (i.e. CO_2, climate, growing season, land use and nitrogen) have stimulated the uptake in middle and high latitudes, whereas in tropical regions mainly CO_2 has affected the C cycle. Land use has contributed to these changes in multiple ways. On the one hand, it has led to less natural forest, and as such to less C storage, for example, in many tropical regions in Asia and South America. And so, avoiding further land-use changes in these regions would effectively limit further increase of atmospheric CO_2 because productive forests would remain. On the other hand, land use can result in more young and re-growing ecosystems (e.g. through the abandonment of agriculture and pasture). In such ecosystems, NPP and soil respiration (and thus NEP) are out of equilibrium (i.e. soil respiration increases slower than NPP), resulting in additional C uptake. Furthermore, land-use emissions lead to a higher atmospheric CO_2 concentration, which increases the natural C uptake through CO_2 fertilization. Net, land-use changes have resulted in a 78% lower C uptake in the USA, averaged over the past three centuries. For most other temperate regions in China, Europe, and Russia, we estimated a 0–15% decrease in NEP due to changes in land use.

Combining land-use and natural C fluxes, we found that many regions in the world functioned as a net land-related C source between 1700 and 2000 (Figure 5-7, Table 5-3b). Exceptions are Europe (approximately C neutral), Russia, and China (sequester 24 Pg C and 10 Pg C, respectively). The development of the estimated trends over time varies, however, across the globe (Figure 5-7, Table 5-3b). Temperate regions are found to be major C sources in especially the 19th century, but turn into C sinks during the 20th century. We found an uptake of 0.8 Pg C yr^{-1} in temperate regions for the 1990s (Table 5-3b). Without land-use emissions from forestry, we estimated a sink of 1.2 Pg C yr^{-1}.These sink estimates for temperate regions are at the low end of the range recently given by Stephens *et al.* (2007) on the basis of inverse model comparison (sink from 0.5 to 4 Pg C yr^{-1}).

On a country/regional scale, the USA emitted 17 Pg C before 1900, with a peak of 0.3 Pg C yr^{-1} at the end of the 19th century, mainly due to changes in land use. This overall C source turned into a C sink around 1940, and has now reached an annual uptake of about 0.2 Pg C yr^{-1}. This current sink in the USA has not yet compensated its estimated historical land-related C emissions. Likewise, the estimated C flux in Europe turned from a small C source before 1910 – emitting in total about 7 Pg C – into a sink, sequestering 8 Pg C over the 20th century, with an annual uptake of 0.13 Pg C yr^{-1} after 1980 (Table 5-3b). This is at the low end of the range from Janssens *et al.* (2003) – based on various measurements – and the high end of the range from House *et al.* (2003) – based on a modeling exercise. Many tropical regions were found to become net C sources in the 20th century, although an increasing natural uptake partly compensates for the large land-use emissions (Figure 5-7, Table 5-3b). The overall tropical net emissions are estimated to be 0.7 and 0.38 Pg Cyr^{-1} for the 1980s and 1990s, respectively (Table 5-3b). The estimated decreasing C source (Figure 5-7) is caused by both a lowering of the land-use emissions (especially in South America) and an increasing natural uptake (especially in Africa). The tropical land-use emissions for the 1990s (i.e. 0.8 Pg C yr^{-1}) are comparable with the estimates of Achard *et al.* (2002) and DeFries *et al.* (2002) (about 1 Pg C yr^{-1}), while the estimated net flux (emitting 0.38 Pg C yr^{-1}) is in line with the findings of Stephens *et al.* (2007), based on an inverse modeling comparison. Without land-use changes, all regions in the world seem to be small (especially tropical regions such as tropical Asia, which sequesters about 3 Pg C) up to large C sinks (e.g. Russia, sequestering 32 Pg C) over the past three centuries.

Overall, these results show that land use has had a significant effect on the C cycle in many world regions.

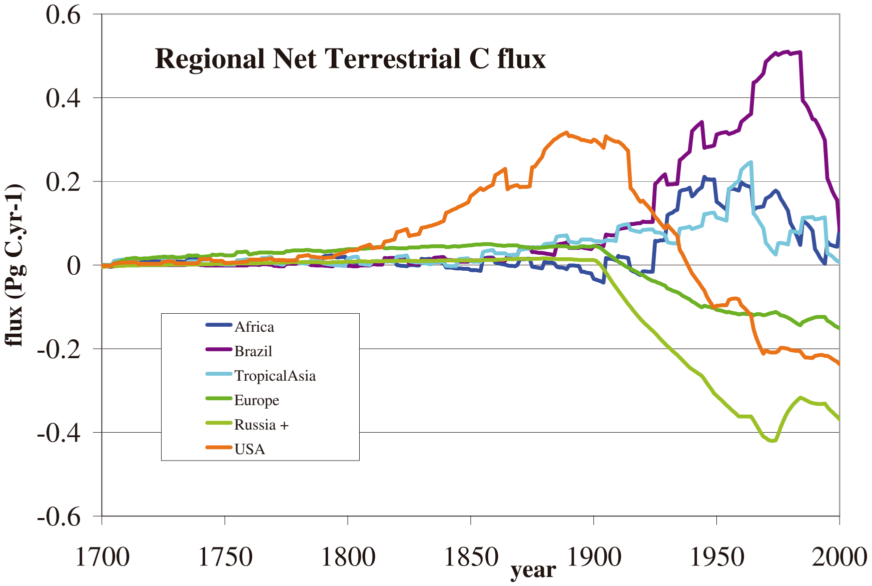


Figure 5-7 **Terrestrial net carbon fluxes for different regions in the world, including deforestation and residual natural sink (Pg C yr^{-1}). Note that a positive number represents a flux from the biosphere to the atmosphere.**

5.5 Conclusion

In this study, we evaluated the role of land use and natural terrestrial ecosystems in the global and regional C cycle for the period of 1700 to 2000 by combining an integrated modeling framework (i.e. IMAGE 2) with a database on long-term historical land-use data (i.e. HYDE). The resulting estimates of land-use related and natural C fluxes contribute to reducing some of the pertinent uncertainties in the historical C cycle dynamics. The strength of the methodology presented is the simultaneous consideration of multiple anthropogenic and biophysical processes in a geographically explicit and transparent manner. For example, we considered explicitly the abandonment of agricultural land use, resulting in a recovery of natural C pools. Likewise, we looked explicitly at the direct effect of deforestation, timber harvest and reforestation on the C cycle, as well as the indirect feedback effects through CO_2 fertilization, climate change and nitrogen deposition. In our opinion this integration is essential because of the closely interlinked processes of the terrestrial C cycle, and their complex temporal and spatial dynamics.

The historical atmospheric CO_2 concentration profile was well reproduced in our study and global and regional terrestrial C fluxes were in line with many other studies. Globally, we calculated that historical land use led to 177 Pg less carbon stored in the terrestrial biosphere compared to a case with no land-use changes. This is more than half the historical fossil fuel-related emissions of 308 Pg C for the period, 1700–2000. Up to 1900 land-use emissions were higher than fossil fuel-related emissions, mainly due to considerable land-use emissions in the USA and Europe, and fossil fuel use that was still low. During the 20th century the C uptake of natural ecosystems increased due to re-growing vegetation, the temperate forest sink, and CO_2 fertilization.

Overall, we found that land-use change played a more important role in the global and regional C cycle over the past centuries than the biosphere response to environmental changes (such as climate, CO_2 effects and nitrogen deposition). In past decades, however, this has changed because environmental change is rapidly changing ecosystems and their C fluxes. The global and regional land-use and natural fluxes also differed significantly between the two different data sources of historical land use. This illustrates the need to improve the accuracy of historical patterns of land use and land cover.

The role of land use and natural processes also varies geographically. In temperate regions like Europe and especially the USA, land-use change played an important role at the end of 19th and early 20th centuries. This led to considerable C emissions and decreased natural uptake rates. This trend changed after 1950 because agricultural abandonment resulted in afforestation. Remaining land-use change emissions came mainly from timber. In tropical Asia, Africa, and South America, the role of land-use changes increased during the 20th century, resulting in considerable losses of natural ecosystems, and associated C emissions and lower C uptake rates. Most of the estimated historical land-use emissions in tropical regions result from land conversion for additional cropland and pastures. Avoiding future land-use changes in these regions may contribute significantly to limiting the further increase in CO_2 concentration, and should therefore be part of international mitigation strategies. But climate policies that focus solely on slowing deforestation or enhancing afforestation will not be sufficient for mitigation climate change, because historical fossil fuel emissions are nearly twice as high as all the land emissions taken together. Nowadays the share of fossil fuel emissions remains dominant.

Given the considerable role of land-use and natural processes in the historical and current terrestrial C cycle, as well as their geographical and temporal variation, there is a need for integrated approaches for energy, the natural environment and land use. This is also valid for projecting the future C cycle.

Chapter 6

The terrestrial C cycle and its role in the climate-change policy [1]

---

[1] This chapter consists of two published sections:

Section A as Van Minnen, J.G., E. C. van Ierland, & G. J. Nabuurs (2003). Terrestrial carbon sinks and biomass in international climate policies; in E. Van Ierland, J. Gupta and M. T. J. Kok.(Eds): I*ssues in International Climate Policy. Theory and policy.*Edward Elgar press**:** 137-168

Section B as Van Minnen, J.G., B.J. Strengers & B. Eickhout. (2008) Evaluating the role of carbon plantations in climate change mitigation including land-use requirements. *Carbon Balance and Management*, submitted

Abstract

The terrestrial biosphere plays also an important role in climate change policy. In order to achieve a stabilization of the greenhouse gas (GHGs) concentrations in the atmosphere – the ultimate objective of the UN Framework Convention on Climate Change (UNFCCC) – it has been accepted that developed countries will partly achieve their reduction commitments by planting new forests or by managing existing forests or agricultural land differently. The objective of this chapter is to discuss issues related to the potential of different land-use options, and the economic and political implications, all in a policy context (e.g. the potential in developing countries under the clean development mechanism CDM). Furthermore, a new methodology is presented in this chapter that quantifies the possible role of C plantations in mitigating the build-up of CO_2 in the atmosphere. This methodology explicitly considers future land-use change around the world, and all relevant carbon (C) fluxes, including all natural fluxes, in evaluating the effectiveness of carbon plantations. Both issues have been generally ignored in earlier studies.

Applying the new methodology for two different baseline scenarios up to 2100 indicates that uncertainties in future land-use change lead to a near 100% difference in estimates of carbon sequestration potentials. Moreover, social barriers preventing carbon plantations in natural vegetation areas decrease the carbon sequestration potential by 75–80%. Nevertheless, carbon plantations can still contribute to slowing the increase in the atmospheric CO_2 concentration, but only in the long term. The most conservative set of assumptions leads to a 27 ppm lower increase of the atmospheric CO_2 concentration up to 2100 and compensates for 5–7% of the total energy-related CO_2 emissions. The net sequestration up to 2020 is limited, given the short-term increased need for agricultural land in most regions and the long period needed to compensate for emissions through the establishment of the plantations. The potential is highest in the tropics, despite the projection that most of the agricultural expansion will be in these regions. Plantations in high latitudes are less effective and should only be established if the objective to sequester carbon is combined with other considerations.

Based on general assessment and the model results, I conclude that C sequestration in plantations and biomass can play a important role in mitigating the build-up of atmospheric CO_2, depending on the rules and accounting methods used and the time frame considered. In addition, there are a number of ancillary benefits for local communities and the environment. Carbon plantations are, however, only effective in the long term. Furthermore, carbon plantations do not offer the ultimate solution towards stabilizing the concentration. They should be part of a broader package of options with clear energy emission reduction measures.

6. The terrestrial C cycle and its role in the climate-change policy

6.1 Introduction

Climate on earth is changing, and this has led to a series of impacts (Schellnhuber *et al.*, 2006). This climate change is most likely caused by the increased greenhouse gas concentration with carbon dioxide (CO_2) as the most important gas (Hegerl *et al.,* 2007). The United Nations Framework Convention on Climate Change (UNFCCC), in its endeavour to limit future climate change and its impacts, aims to "stabilize greenhouse gas (GHG) concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (Article 2, UNFCCC, 1993). Many studies have compared emission reduction strategies to achieve different stabilization levels of CO_2 and quantified their consequences (e.g. Morita *et al.*, 2001). Most of these studies concentrate on reducing energy-related CO_2 emissions and ignore abatement options that enhance CO_2 uptake (or increase C sinks) by the biosphere. Such uptake also slows down the concentration increase in atmospheric CO_2.

The Kyoto Protocol, drafted in 1997 and entered into force in 2005, includes quantitative targets for industrial countries (the so-called "Annex B") to limit the emissions of six GHGs (CO_2, CH_4, N_2O, and three fluorinated gases) by the 2008–2012 period. In addition to calling for a reduction in emissions from fossil fuel burning, the Kyoto Protocol provides explicit opportunities for Annex B countries to partly achieve their reduction commitments by planting new forests or by managing existing forests, or agricultural land differently (so-called land-use, land-use change and forestry measures; LULUCF).The presumption of these LULUCF options is that avoiding a build-up of CO_2 (or other GHGs) in the atmosphere will also lead to avoidance of climate change, regardless the origin of the carbon. After the Kyoto Protocol was signed, a number of technical issues regarding the use of carbon plantations in achieving the country commitments remained open. For example, it has been unclear how to quantify the LULUCF potential, both in the short and the long terms. *Furthermore,* criticism on establishing new forests (so-called carbon plantations) as a mitigation strategy were related to the permanency of sequestration and whether the sequestration is additional to default developments (e.g. Noble & Scholes, 2000). Permanency is uncertain, since the pressure on land for other purposes than carbon plantations may increase considerably in the near future. The FAO, for example, projects considerable increases in arable land needed for food production (Bruinsma, 2003), whereas land requirements for modern biofuels are increasing considerably as well (Hoogwijk *et al.*, 2005). Furthermore, the Kyoto Protocol clearly states that activities should not be in conflict with existing conventions, such as the Convention on Biological Diversity. Thus land-use changes that drive losses in biodiversity should also be prevented (MA, 2005).

This chapter consists of two parts, each dealing with possible role of LULUCF activities, in general, and carbon plantations, in particular, in mitigating the build-up of CO_2. The objective of section A is to discuss in general terms issues related to the biophysical potential of different land-use options, as well as the economic and political implications, all in a policy context. Firstly, I will identify why the LULUCF options were politicized and why they have become controversial. Secondly, I will briefly quantify the potential of using C sinks and biomass as mitigation options. Thirdly, I present the economic issues of using sinks and biomass systems, showing, for example, the economic characteristics of land-use projects under the clean development mechanism (CDM). Fourthly, I discuss political views with respect to the inclusion or exclusion of land-use options in mitigating climate change. Finally, I will summarise remaining issues and present conclusions related to using C sinks and biomass systems as mitigation options. In section B, I present a new methodology that quantifies the possible role of C plantations in mitigating the build-up of CO_2 in the atmosphere. The Kyoto Protocol has resulted in several studies estimating this potential. The IPCC's special report on LULUCF activities, for example, suggests that there is a potential to sequester an additional 87 Pg C by 2050 in global forests alone (Watson *et al.*, 2000). Other studies even suggest that land-based mitigation could be more cost-effective than energy-related mitigation options, and could provide a large share of the total mitigation (McCarl & Schneider, 2000; Sohngen & Mendesohn, 2003). However, it is often difficult to compare the results of these studies because they differ in terms of definitions, and methods used. Furthermore, studies determine the sequestration potential in specific regions or specific land-cover types (e.g. Hamilton & Vellen, 1999; Nabuurs *et al.*, 2000; Sathaye *et al.*, 2001). Finally, there are studies that incorporate crude assumptions for future land-use change. For example, Sathaye *et al.* (2006) based their projections of C sinks on linear extrapolation of continuing deforestation and afforestation rates, whereas Sohngen & Sedjo (2006) only considered an increase in forest product demand, discarding future food demand. The methodology presented in section B quantifies the possible role of C plantations around the world in mitigating the build-up of CO_2 in the atmosphere at different cost levels and assumptions; it also takes into account the aforementioned limitations and concerns. I specifically address the issue of net carbon sequestration, including the continued carbon sequestration of the original natural vegetation. Moreover, I only consider the carbon sequestration potential in regions that are not used for other ecosystem services (like food supply), and do include future land-use change. The methodology has now been implemented in the IMAGE 2 model (Integrated Model to Assess the Global Environment; MNP, 2006) to show the long-term potential in 18 different world regions.

Section A: Terrestrial carbon sinks and biomass in international climate policy

6.2 Why is the C sink issue so controversial? Open questions, remaining issues and definitions

The 1997 Kyoto Protocol represents a milestone in the negotiations on climate policy, with binding targets being established. Especially with respect to sinks and biomass, the Protocol is not always explicit (Schlamadinger & Marland, 2000). This has led to considerably different views among countries (Metz *et al.*, 2001). Since 1997 political progress has been made in resolving these issues, especially during the meeting in Bonn in July 2001 (COP 6 bis). However, several issues are still open, such as the permanence of sink projects in non-Annex B countries. In addition, there are several reasons for the terrestrial carbon sinks becoming so politicized and controversial:

- Even conservative estimates of the sink and biomass capacity show considerable potential in meeting the Kyoto commitments. Some countries fear that the use of sinks as a mitigation option might reduce the incentive in some countries to reduce their fossil fuel emissions.

- Countries with large forests and agricultural areas were assumed to be able to meet their reduction targets easily through sinks alone. In some cases, they would even be able to increase their fossil fuel emissions. But it was felt that this would not equally distribute the burden of reducing emissions.

- The accounting, prevention of leakage, etc., could lead to a huge global bureaucracy, keeping track of all flows of carbon in each little parcel of land.

- Different methods have been proposed to quantify the sink and biomass potential. These methods give different outcomes, resulting in uncertainties and opportunities for policy makers.

- The terrestrial carbon cycle is inherently dynamic, and only partly influenced by human activities. Other contributing factors include, for instance, variations in weather, climate, and natural disturbances. It is within this uncertain framework that binding targets have to be discussed.

6.3 Quantification of C sinks and biomass use

Terrestrial sinks and biomass are considered important for the global carbon cycle and may thus contribute to solving the climate problem. One way of categorizing related land-use activities is by grouping them according to the mechanisms through which they affect carbon stocks and flows and, thus, the CO_2 concentration in the atmosphere. In principle, there are three basic mechanisms (Kauppi *et al.*, 2001):

1. carbon sequestration, i.e. sequestering carbon in ecosystems (including soils) and products;

2. carbon conservation, i.e. avoiding emissions related to land use by protecting existing carbon pools (e.g. through forest management);

3. carbon substitution, i.e. the replacement of fossil fuels by biomass energy.

6.3.1 Accounting rules, indicators and measurement methods

An accounting system is needed to record and report changes in carbon stocks from applicable land-use activities. According to the Kyoto Protocol, this system, which has to be defined by 2005, should be transparent, consistent, verifiable and relatively accurate in quantifying the potential C sink for Annex B countries during the first commitment period. But what should such an accounting system look like? Various factors have a strong influence on the sink potential of an activity. Matthews *et al.* (1996) and Nabuurs *et al.* (1999), for example, showed that the methods and criteria used within an accounting scheme are important for determining the net potential of sinks and biomass as mitigation options. There are two reasons for this.

Firstly, within the climate arena, two different accounting approaches have been discussed that could meet the requirements of transparency, consistency, and verifiability. These are: (1) a *land-based* and (2) an *activity-based* accounting scheme (Watson *et al.*, 2000). The two schemes have both advantages and disadvantages (Box 6.1).

Secondly, the question is which stocks or fluxes should be considered and how should they be compared in 2008-2012 to those considered in 1990 (Box 6.2). This is important, because the land-use change and forestry (LUCF) sectors include, contrary to other sectors, sinks and emissions of carbon. Should only the sink be considered or should the net C flux (thus both sinks and emissions) be taken into account? Different proposals have been made (see Noble & Scholes, 2000, for details). The Kyoto Protocol specifies what is often referred to as the “gross–net” approach. In this approach, assigned amounts are based on gross emissions in 1990 (not corrected for sinks). However, emissions in the first commitment period are based on net emissions (i.e., countries can get benefits for their sinks). The problem with the “gross–net” approach is the large uncertainty of sinks, which would only count in setting the target. The sinks in the first commitment period may be very large, especially if the approximately 2.3 Gt C.yr^{1} of net carbon sequestration in the biosphere is identified as especially occurring in Annex B countries.

Box 6.1: Accounting methods

The basis of the "land-based" accounting scheme is that, first, applicable activities are defined, and then followed by identifying a "Kyoto land" where these activities may occur. This approach involves full carbon stock changes for this particular land between 2008 and 2012. Adjustments can easily be made on baselines, leakage, etc. A disadvantage of a land-based accounting system is that it can be difficult to separate human-induced stock changes from indirect effects. Furthermore, fluxes in non-CO_2 gases cannot be estimated (Noble & Scholes, 2000).

The "activity-based" approach starts with defining certain activities, followed by accounting for changes in C stocks for each of the applicable activities (per unit area and time). The stock changes are then multiplied by the area on which an activity occurs and the number of years the activity is applied. A disadvantage of the "activity-based" approach is that an area could potentially be counted more than once if multiple activities occur and the activities are not supplementary, which could result in inaccurate accounting. Alternatively, each land unit can be subject to only one activity.

At the COP 6bis in Bonn, parties agreed to apply the so-called "net–net" accounting approach for activities under Art. 3.4. This approach is based on comparing the net emissions in the first commitment period with the net emissions in 1990. Thus, terrestrial sinks are considered in both as the target. Some parties recognize that this "net–net" approach would make it difficult for countries with a large sink in the base year (1990) to maintain (or even increase) the size of the sink into the commitment period.

Regardless of the accounting system that will become accepted, the potential sink should be "reported in a transparent and verifiable manner". Several methods have been developed to quantify changes in terrestrial carbon stock and fluxes (e.g., Nabuurs *et al.*, 1999; Sarmiento & Wofsy, 1999; Dolman *et al.*, 2001; see Box 6.3).

These methods include constraints from atmospheric chemistry (e.g., Fan *et al.*, 1998), various models (e.g., Schimel *et al.*, 2000), land-use book-keeping (e.g., Houghton *et al.*, 1999), flux towers (Baldocchi *et al.*, 2000; Valentini *et al.*, 2000), and forest inventories (Nabuurs *et al.*, 1998; UN-ECE/FAO, 2000). What these methods all have in common is that they show a highly dynamic terrestrial biosphere. In addition, they bring with them two factors that determine the carbon-sink potential in an area: the type and condition of the ecosystem, i.e. species composition, age and structure, site conditions like soils and climate, and management) and the (previously mentioned) question of whether changes in C stocks or C fluxes should be considered for quantifying the sink potential (Box 6.2). Important differences between the methods are that they operate on different spatial and temporal scales, include different C stocks and describe different processes. Thus, full accounting of the carbon balance inevitably requires a multi-method exercise (Watson *et al.*, 2000).

Box 6.2: Indicators to quantify the sink potential

In general, the sink potential of an area or activity can be quantified by measuring either changes in C stocks or C fluxes. An advantage of considering changes in fluxes is that fluctuations in carbon sequestration or release between years can be considered. This may be important for determining the change during the different commitment periods. A disadvantage of the flux measurement is that it only measures the dynamics over a relatively short time period.

For the *stock approach*—deeply rooted in the field of forestry and agriculture (e.g. forest inventories)—one can consider changes in above-ground biomass, possibly expanded with wood products. This approach is highly verifiable; however, the method is weak at accounting for large amounts of carbon stored in different soil compartments. This could be solved by considering the *soil carbon pools and soil processes* as well, although it is complicated by the lack of accurate soil data (which is important in determining the baseline) and the difficulty in verifying small changes in these data.

There is also a variety of indicators to measure fluxes. One can consider the net primary production (NPP) or total growth of an ecosystem, i.e., the CO_2 taken up through photosynthesis minus the CO_2 loss due to plant respiration. Similar to the approach mentioned above that measures above-ground biomass, the NPP approach is highly verifiable, but does not take soil processes and pools into consideration. If changes in pools of soil carbon become part of the accounting scheme, net ecosystem productivity (NEP) would be an alternative measure. NEP describes the net carbon uptake of an ecosystem (including soils), assuming no changes in land use or cover. A disadvantage of using NEP is that it is difficult to verify. This problem is even larger for net biome productivity (NBP), which denotes an ecosystem's net carbon uptake/release. Compared to the NPP and NEP fluxes, NBP is relatively small (about 1 and 10%, of NPP and NEP, respectively). The advantage of NBP is that, compared to the NEP approach, it also considers other processes that lead to carbon loss (e.g. harvests and natural disturbances). With regard to the Kyoto Protocol, NBP still does not account for the fate of the original vegetation and its carbon budget. This could, however, be important if someone wants to quantify the net implications of ARD activities. The surplus potential productivity (SPP) has been developed in an attempt to account for the "real" carbon gain of planting a Kyoto plantation (Onigkeit *et al.*, 2000). SPP is defined as the NEP of a growing Kyoto forest, and corrected for the carbon uptake that would have occurred if the original vegetation had remained at that location and the release that results from clearing the original vegetation for planting the forest. A positive SPP value indicates that it is worth planting a Kyoto plantation, since it will take up more carbon from the atmosphere than the original vegetation.

Box 6.3: Measurement methods

Various techniques have been developed to quantify terrestrial carbon sources and sinks. All of them have both advantages and disadvantages.

Inventories were designed to sample the status of forest resources across large regions. A variety of assumptions are required to convert inventory measurements to carbon budgets. Their main limitation is related to the effort required to make them, which makes frequently repeated inventories relatively rare outside Annex B countries. Furthermore, inventory data are often difficult to compare between countries because of differences in definitions, for example.

The strength of measurements (e.g., through *eddy flux towers*) is the integrated signal from all of the mechanisms affecting the net carbon production in the ecosystem, the ability to measure gas fluxes directly and the stability of the system. But these measurements are local and limited to a few sites, and thus do not capture the variability of carbon flux conditions across the broader landscape. In addition, flux tower measurements have a temporal disadvantage. The towers may measure a C sink for a number of years but may fail to measure a disturbance.

Large-scale measurements (e.g., though air sampling) and remote sensing. Both are potentially useful for upscaling local measurements and quantifying large-scale carbon fluxes, especially if coupled to carbon-cycle models. These methods are very applicable in quantifying C fluxes in areas with no ground information, for example, in many tropical areas. However, their accuracy is often questioned. Another problem is that they are applicable to quantifying carbon pools below ground (e.g. because of the number of processes involved and the spatial variation). In addition, validation by ground-based estimates is required to come up with reliable C-sink potentials.

Atmospheric *inversions* constrain the magnitude of terrestrial carbon sinks, but their ability to discern the responsible mechanisms or the exact location of the observed sink is limited.

There are different *modeling approaches* to quantifying ecosystem dynamics and related C fluxes. Process-based models, for example, can explore the importance of the ecosystem's physiological responses to climate variability or increasing CO_2. But they often focus on specific segments without considering natural or human-induced disturbances in realistic detail. In contrast, models of land-use change focus on the effects of human land use and are insensitive to changes in ecosystem physiology. In general, the use of models to estimate changes in C fluxes may lead to less transparency because models differ and are often very complex and difficult to understand.

Based on Houghton et al. (1999); Nabuurs et al. (1999); Watson et al. (2000).

6.3.2 The potential of C sequestration and biomass to mitigate climate change

The different accounting systems, methods and indicators make an accurate quantification of the current and future potential for carbon sequestration in the biosphere difficult. In this section, we discuss various estimates of the C-sink potential and the potential to offset emissions through biomass energy, as given in literature.

Firstly, it is important to discuss the role of the terrestrial biosphere in the global carbon cycle, since this determines the natural potential for carbon uptake. The net uptake of the terrestrial biosphere shows significant diurnal, seasonal, year-to-year and even centennial dynamics. In the last two decades, the biosphere has served as a sink (Table 6-1), taking up approximately a quarter of the carbon released from fossil fuel combustion (Prentice *et al.*, 2001). There is an indication that this uptake is specifically triggered by indirect human activities (especially the re-growth of young forests after deforestation during the first half of the 20th century, in combination with CO_2 and nitrogen fertilization (Dolman *et al.*, 2001) and can be maintained for a number of decades. There is, however, also an indication that this uptake may diminish around 2100 (Cramer *et al.*, 1999), which, in turn, will have consequences for future commitment periods in which atmospheric concentrations of CO_2 should be stabilized.

Many studies show that, in contrast to the natural sink, the potential for a human-induced carbon sink may be large in the future. This would imply that a large part of the Kyoto targets could be fulfilled by using sinks. However, the sink potential depends on the time horizon, definitions and eligible categories of land-use options and indicators chosen.

Table 6-1 Global CO_2 budget for the periods 1980–1989 and 1990–1999 (Gt C yr^{-1})

	Carbon flux	1980 to 1989	1990 to 1999
1	Emissions from fossil fuel combustion and cement production	5.4± 0.3	6.3± 0.4
2	Land-use emissions	1.7 (0.6–2.5)	NA (1.6±0.8)[1]
3	Storage in the atmosphere	3.3± 0.1	3.2± 0.1
4	Uptake by the ocean	1.9± 0.6	1.7± 0.5
5	Net uptake by terrestrial biosphere (=[3+4]-1)	-0.2± 0.7	-1.4± 0.7 (-0.7±1.0)[1]
	Total terrestrial uptake (= 5–2)	-1.9 (-3.8 to 0.3)	NA (-2.3± 1.3)[1]

[1] According toPrentice *et al.*, (2001) insufficient data (NA) are available. As an indication, numbers from Watson *et al.* (2000) for the period of 1989–1998 are presented in brackets. Source Watson *et al.*, 2000; Prentice *et al.* (2001)

The first issue is the time horizon, i.e., whether a short- or a long-term perspective is considered (Figure 6-1). For the short term (e.g. up to the first commitment period) the sink capacity under article 3.3 (i.e. forestation activities) may be limited in most Annex B countries (some countries have even accounted for a source of C). Areas for planting forest will hardly become available and it will take years before new forests can store a significant amount of carbon, while even a small area of deforestation results in debits. In the long term it could be efficient to plant forests. Studies indicate that vast areas will become available for planting forests in Europe and North America up to 2050 because of agricultural and environmental policies. Forests planted in these areas will store significant amounts of carbon. In addition, the carbon storage in the soil compartment of a Kyoto forest could increase for decades.

A second issue in determining the potential domestic sink in Annex B countries is the type of activities that can be accounted for under Article 3.3 (ARD) and 3.4 (i.e. additional activities). The strict case of limiting activities only to ARD significantly reduces the sink capacity (Table 6-2) due to the reasons mentioned above. Allowing activities under Art. 3.4 as well increases the magnitude of the carbon sink. The sink potential depends on decisions made about the categories of activities allowed (see Figure 6-2 and Box 6.4). If all activities are allowed, the potential in Annex B countries is estimated to be about 0.5 and 1 Gt C yr^{1} in 2010 and 2040, respectively (Watson *et al.*, 2000). Analyzing the individual activities shows that for the next 50 years, changes in forest management could result in an additional uptake of 0.5 Gt C yr^{1} (Watson *et al.*, 2000); better management of agricultural soils could result in 0.4–0.6 Gt C.yr^{1} (Batjes, 1998; Lal & Bruce, 1999; Kauppi *et al.*, 2001). Finally, allowing sinks under CDM would also considerably increase the potential of sinks (Table 6-2).

Table 6-2 Range of estimated potential of most important sink categories for the first commitment period and comparison to estimated differences between baselines and assigned amounts for OECD countries

Category	Min potential ($MtC.yr^{-1}$)[1]	Max potential ($MtC.\ yr^{-1}$)	Remarks
Art 3.3	5	140	High end due to application of Art 3.7 by some countries
Art 3.4	50	500	Based on IPCC assumptions about percentage of lands covered for various land-use activities; extending it to large parts of the land will drastically increase high amount
Sinks in CDM	50	130	High end based on IPCC assumptions about percentage of lands in developing countries where land-use activities could be undertaken (afforestation, reforestation and land-use practices) and a conservative estimate that only 10% of that potential can be tapped by project-based activities during the first commitment period; bringing more land in or increasing the project area can significantly increase the high amounts. This does not include avoided deforestation (good for a maximum of 1600 Mt C/yr) given that this is strongly opposed by many countries.
OECD "demand"	750	1200	This is the estimated difference between baseline emissions in the commitment period and assigned amounts without any other action to close that gap (Vrolijk et al., 2000)

source: Metz et al. (2001), Watson et al. (2000); Noble & Scholes (2000).

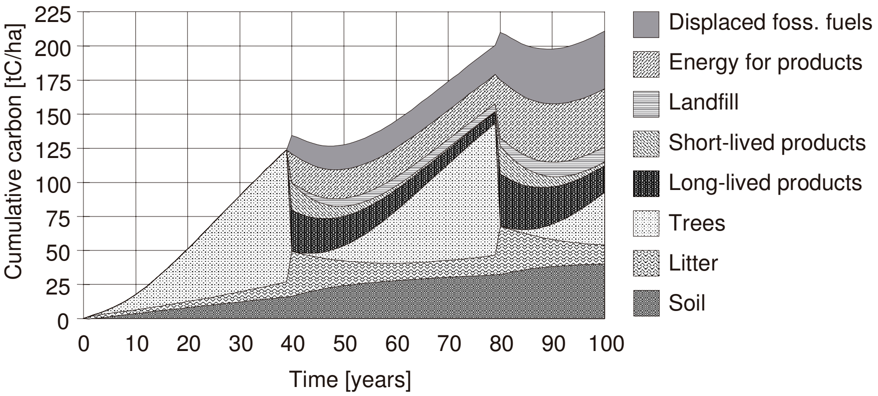


Figure 6-1 **Schematic representation of the cumulative carbon-stock changes and avoided emissions for a scenario involving afforestation and harvest. These are net changes, for example, the diagram shows savings in fossil-fuel emissions with respect to an alternate scenario that uses fossil fuels and alternative, more energy-intensive products to provide the same services (Adapted from Marland & Schlamadinger, 1999; Kauppi *et al.*, 2001).**

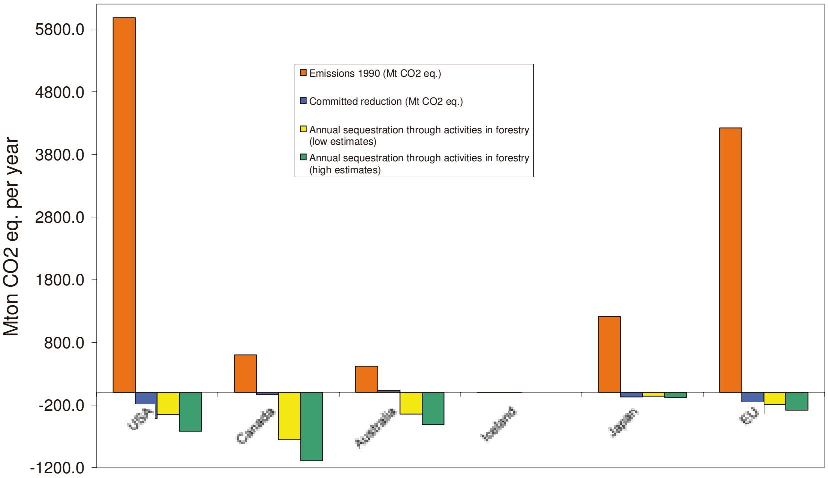


Figure 6-2 **Potential carbon sink in forests for selected countries and forest-management activities under Article 3.4 (Mt CO_2 equivalents), relative to commitments and assigned amounts under the Kyoto Protocol. Estimates include all applicable forestry activities and assume adoption on an average of about 10% of available area. Estimates are derived from the "access to country-specific data" (ACSD) tool. The values, presented here for illustration only, vary among assumptions used and chosen set of measures. Values for the four bars for Iceland are 2.6, -0.1, -0.2 and -0.3, respectively (Adapted from Nabuurs *et al.*, 2000).**

Box 6.4: The EFISCEN model

The European forest information scenario (EFISCEN) model is an area-based matrix model used to address, among other things, the impact of climate change and the potential carbon sequestration of European forests. With EFISCEN, insights can be gained in the development of forests in Europe (Nabuurs *et al.*, 2001). The forests were replanted in the course of the 19th and 20th centuries, and are now mostly under 80 years of age. It is the history of these forests that determines their present and future capacities as a carbon sink. Figure B1 shows the effect of the vegetation rebound in terms of age-class development.

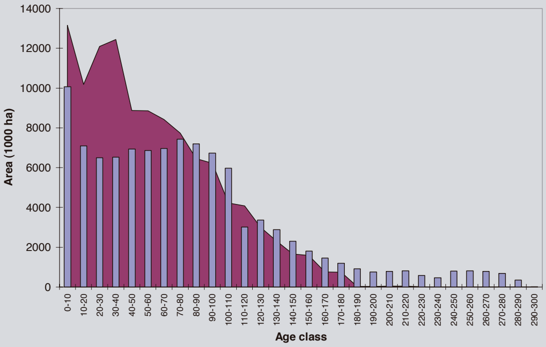


Figure 6-B1 Age-class distribution of European forests in 1990 (filled area) and 2090 (bars), as simulated with the EFISCEN model (Nabuurs *et al.*, 2001).

EFISCEN demonstrates that even without climate change, there is a continuous build-up of the growing stock (thus, **sink**), assuming a certain annual increment and felling level. The average growing stock is shown to increase from 137 m^3 ha^{-1} in 1990 up to 245 m^3 ha^{-1} in 2050. Climate change in Europe could lead to an enhanced build-up of growing stock, up to 282 m^3 ha^{-1} in 2050 (Figure B2). It is within this autonomous vegetation rebound that the additionality of Kyoto measures must be decided upon.

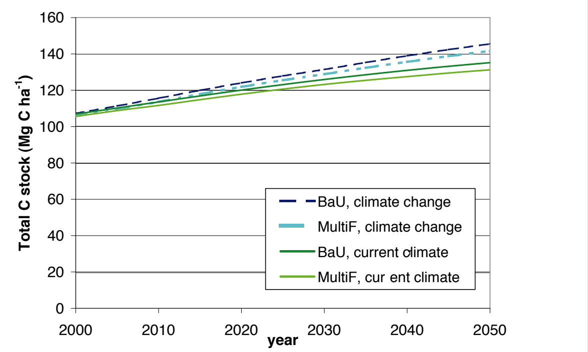


Figure 6-B2 Average development of total carbon stock (tree biomass, soils, and wood products) for European forests from 1990 to 2050 under two alternative scenarios of management and climate (BaU = Business as usual; MultiF = Multi functional management).

An issue related to the discussion about the carbon-sequestration activities under Articles 3.3 and 3.4 is the use of biomass as a source for energy or as a substitute for more energy-intensive materials. Such biomass use can also significantly contribute to a reduction of fossil fuel emissions (Hall *et al.*, 1991; Marland & Schlamadinger, 1997, Nabuurs *et al.*, 1998; Kauppi *et al.*, 2001). The use of abandoned forest products for energy rather than disposal as waste could provide additional opportunities for displacing the use of fossil fuels (Apps *et al.*, 1999). Recent studies indicate that in the next 30 to 40 years, the total potential for biomass production could increase up to 300–400 EJ yr^{-1} (Faaij & Agterberg, 2000; UNDP, 2000; Watson *et al.*, 2000), which is close to the world's current energy production of approximately 400 EJ (resulting in emissions of about 5.4 Gt C yr^{-1}). The use of biomass to substitute for more energy-intensive materials may be limited with current policies (Karjalainen, 1996; Marland & Schlamadinger, 1997, Nabuurs *et al.*, 1998). Recent studies, however, show that the long-term effect would be large if new, effective policies to stimulate the use of wood as a basic material would be initiated (Hekkert, 2000; Gielen *et al.*, 2001).

In addition to the potential contribution of biomass, the advantages of using biomass are its relatively equal distribution across the world and its relatively low price (see next section). In addition, it does not have some of the difficulties of carbon sequestration (e.g. permanence is not a question because biomass substitutes carbon emissions from the use of fossil fuels), although some other disadvantages remain (e.g. the competition for land).

A final topic that determines the net land use-related carbon potential is whether or not such projects are acceptable in non-Annex B countries through CDM. The issue of accounting for CDM projects is controversial because, on the one hand, the potential sink is huge (Table 6-2, section B), but on the other, there are many disadvantages (see also section 6.5).

6.3.3 Side-effects of carbon conservation, sequestration, and biomass activities

Activities to stimulate carbon conservation, sequestration or fuel substitution provide significant socio-economic and environmental side-effects (Makundi, 1997; Brown, 1998; Watson *et al.*, 2000). These side-effects do not directly determine the sink potential of an activity (i.e. the net effect on atmospheric CO_2 concentrations), but they could contribute to the discussion about the usefulness of an activity.

Side-effects can be positive or negative. Often, the net result depends on the design and implementation of the project (WBGU, 1998; Watson *et al.*, 2000). Further, the result also depends on the type of activity. Carbon conservation, for example, often improves biodiversity, whereas afforestation activities may negatively affect the biodiversity in a region because of the relatively low number of species they support and the introduction of exotic species. Only if the plantations are established in grassland areas or on degraded land, can the net effect on biodiversity be limited. Similarly, carbon conservation often results in less deforestation. The effect of ARD projects on the deforestation in a region depends on the original land cover, i.e. whether or not the project starts with the harvest of virgin forests (WBGU, 1998).

In general, the positive effects of many carbon-sequestration and biomass activities are the potential to improve soil properties, to protect watersheds, and to reduce the pressure on remaining natural forests. Further, land-use activities may be accompanied by the introduction of new land-use activities and technologies, promoting sustainable agricultural practices. A particularly positive side-effect associated with carbon-substitution projects is the possibility for local communities to obtain decentralized, more stable, energy-supply systems.

The negative environmental and socio-economic impacts associated with land-use activities are often related to their possible impact on the local community. For example, afforestation activities may compete for land for which a community has other priorities (such as agricultural production Lugo, 1997). Further, concern is often expressed because of the non-permanence of afforestation activities.

To summarize, activities aimed at carbon conservation, carbon sequestration, or fuel substitution are neither inherently good nor bad in terms of possible side-effects. The net result highly depends on their design and implementation, the type of activity, and the involvement of the local community.

6.4 Economic aspects

The main economic issues on offsetting emissions through carbon sinks or energy from biomass concern the potential change in emissions and the costs of the various options, including ancillary costs and benefits. Since the potential and the costs differ for various regions in the world, an important issue is whether the low-cost options that are available in developing countries and Eastern Europe can be used through the clean development mechanism (CDM) and joint implementation (JI), respectively (see next section).

The economic costs of terrestrial sinks and energy from biomass are calculated on the basis of the required investment costs and the annual operation and maintenance costs of afforestation, reforestation, reduced deforestation, or farm management, including the costs of alternative uses of the land. In comparing alternative options, it is necessary to estimate costs and revenues over the period of the projects involved and to discount to present values.[2] For agroforestry, the growth characteristics of the forest and the rotation period are considered in addition to the lifetime of a project,

---

[2] The net present cost of a project can be calculated as $NPC = I_0 + \sum [e^{-rt} * (C_t - B_t + OC_t)]$
Where NPC = net present cost, I_o = investment in base year, r = discount rate, C = annual operations and maintenance costs, B = annual benefits, OC = annual opportunity costs, and t = time (0,...,T). The costs per metric ton can then be calculated as the NPC divided by the total net quantity of carbon stored in the sink over the lifetime of the project.

and assumptions are needed about the use of wood products, their lifetime and the waste-management systems at the end of their life cycle.

On the basis of various case studies (see Box 6.5 for an example for Mexico), cost functions have been constructed to indicate the potential and cost of various options for reducing or offsetting greenhouse gas emissions by means of carbon sinks or biomass energy.

Box 6.5: Mexico—Agroforestry

A case study on forestry and agroforestry in the Central Highlands of Chiapas in Mexico is presented in De Jong (2000). He analysed the costs of reducing GHG emissions by forestation and management of fallow land, agricultural land and pasture in Mexico. The study considers the private costs of these management options and the opportunity costs of agricultural income foregone. It pays extensive attention to the risk of carbon leakage, i.e., the possibility that additional deforestation will take place at another location, outside the project boundaries.

The study shows that reforestation can result in large reductions of CO_2 emissions at relatively low costs (US$ 5 to 20 per ton of carbon). Within this range, measures involving forestry and agroforestry in the relevant study area could mitigate from 1 Mt C to 42 Mt C, with a maximum economic supply of carbon sequestration of about 55 Mt C at US$ 40 per ton C. If indeed the forestation project is additional and no carbon leakage takes place, the project would be useful for CDM. However, it is not clear whether reforestation would occur anyway or not at all if no climate policies were implemented. It is therefore difficult—if not impossible—to make a scientific judgment about the additionality of the project.

6.4.1 Costs of biomass

Biomass contributes significantly to the world's energy supply, probably accounting for about 45 EJ a year (9% to –13% of the world's energy supply). Estimates for the contribution of biomass to future energy demands shows that biomass may play an important role (up to 300–400 EJ yr^{-1}, see previous section), thus contributing to offsetting current emissions from fossil fuels. It is estimated that with agriculture modernized up to reasonable standards in various regions, and given the need to preserve and improve the world's natural areas, 700–1400 million hectares may be available for biomass production well into the 21st century (UNDP, 2000). The economic costs of biomass energy systems differ from region to region, depending on the price of land, labour and capital, and the local efficiency of technologies and management. Prices range from US$ 1.5–2.0 per GJ in Brazil, to US$ 4 per GJ in some parts of Europe. With biomass prices of about US$ 2 per GJ and state-of-the-art combustion technology at a scale of 40–60 megawatts of electricity, biomass could result in electricity production costs of about US$ 0.05–0.06 per kilowatt-hour (UNDP, 2000). Whether large-scale biomass energy systems will become competitive depends on cost reductions through technological progress and the future level of carbon prices. Carbon prices in the range of US$ 20 to US$ 60 and above per ton of CO_2 equivalent would definitely provide strong incentives to further expand energy supplies from biomass in the USA, Europe and developing countries.

6.4.2 Carbon sequestration and biomass energy in the USA

McCarl & Schneider (2000) used the Agricultural Sector Model to analyse the potential carbon emission sequestration in the agricultural sector in the USA at varying carbon price levels. They estimated a potential for the USA of about 350 million metric tons (Mt) of carbon equivalent at a price of US$500 per ton C equivalent. However, at lower prices (in the range of US$50 or 100 per ton C equivalent), the potential remains around 125 Mt of carbon equivalent. Figure 6-3 shows the total carbon emissions avoided by the use of different land-use options. The figure also shows a relatively low potential for sequestration at carbon prices below US$60 per ton of carbon equivalents but a rapid increase for biomass for power plants.

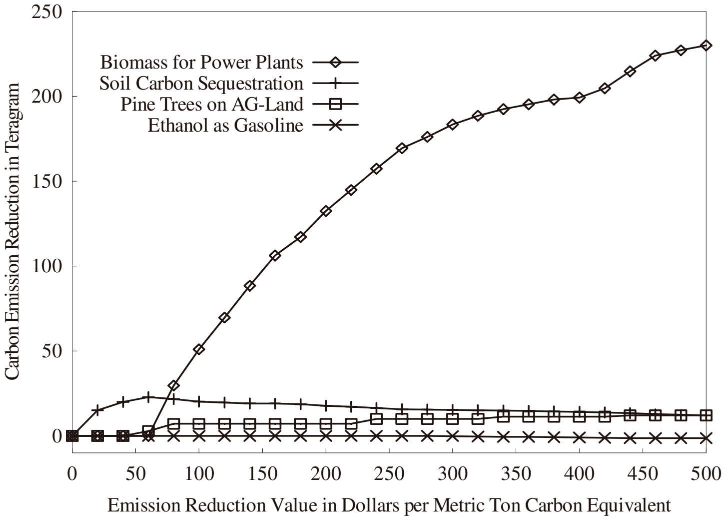


Figure 6-3 Potential and costs of reducing carbon emissions in dollars per metric ton of carbon equivalent (McCarl & Schneider, 2000).

6.4.3 Carbon sequestration in soils

Carbon sequestration in soils is an interesting option, especially at low carbon prices. Batjes (1998) indicates the global potential for sequestration through improved soil management from 580–800 MMT C per year over the next 25 years. There are only a few estimates regarding the costs of carbon sequestration in soils. The study of McCarl & Schneider (2000) reports a potential for the US of about 30 Mt of carbon equivalent for a carbon price of US$40 per metric ton of carbon equivalent and above (Figure 6-3). Further studies should reveal how much could be sequestered at what cost in other regions of the world.

6.4.4 Emission offsets from forestry compared to emission-reduction options

How do emission offsets from forestry compare to other options for reducing emissions?
Although the different studies have been based on different assumptions, it is still interesting to compare the cost estimates reported for various types of land-use activities. Figure 6-4 shows that forestry in developing countries is a low-cost opportunity for large-scale carbon sequestration, provided that transaction costs are kept within reasonable limits and that no excessive carbon leakage occurs (Kauppi *et al.*, 2001). In the short term, fuel-switch also provides good opportunities at low costs. Figure 6-4 also shows that renewable energy is relatively expensive, and that forestry in OECD countries offers limited potential for offsetting CO_2 emissions at a low price (maximum amount that can be offset by forestry in OECD countries is 250 Mt CO_2 at a price of US$50 per ton of CO_2). Thus, carbon sequestration and biomass can provide opportunities to reduce the net accumulation of carbon in the atmosphere at relatively low costs (in the range of US$0–50 per ton of CO_2), but only for a relatively modest quantity.

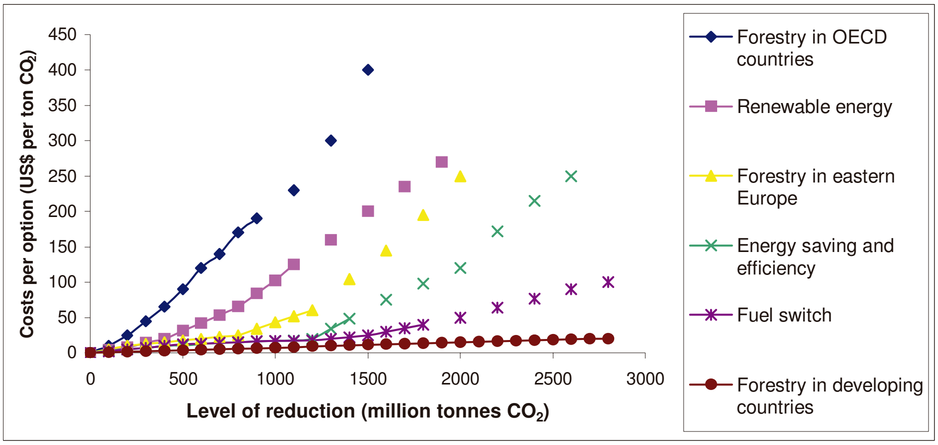


Figure 6-4 **Indicative curves of costs (US$ per ton CO_2) of emission reduction or carbon sequestration according to level of total reduction. The curves show cost differences among world regions between comparable options. However, costs per option are also reported to vary considerably, and at comparable total levels of reduction. This is mainly because studies on costs have not been carried out in the same way. In some options, a net monetary profit may also be made (i.e. costs may also be negative) Source: Kauppi *et al.* (2001).**

6.5 Sinks and biomass energy as part of joint implementation (JI) and the clean development mechanism (CDM)

The Kyoto Protocol offers opportunities for Annex B countries to achieve parts of their emission reductions through land-use measures in other Annex B countries (as part of joint implementation) or non-Annex B countries (as part of the clean development mechanism). Given regional cost differences, it is interesting to discuss the role of JI and CDM in using the options of carbon sinks and biomass energy. Because of differences in the cost of reducing emissions in various countries in the world, cost effectiveness can be enhanced by means of these mechanisms. However, serious problems may occur with their practical implementation. CDM accounting projects, especially, have raised specific concerns. First, they are surrounded by large uncertainties in basic data, the permanence of the carbon storage, and the problem of additionality (i.e. crediting reductions that would have occurred anyway) and leakage (i.e. crediting sink activities, the gain of which becomes counterbalanced by carbon losses outside the project area). Second, the effectiveness of land-use projects under CDM is difficult to monitor and verify. Various problems remain for the actual implementation of such projects. Clear methods should be developed to establish the net additional reductions of the emissions of various projects. This holds both for projects focused on sustainable energy (like solar, wind, hydropower, and biomass) and for projects for carbon sequestration through afforestation, reforestation, or reduced deforestation. Special attention will be required for the various methods used in establishing the baseline emissions and for tackling the possibility of carbon leakage, i.e., the option that additional GHG emissions will occur elsewhere as an undesired side-effect of a project.

At present, more and more developing countries are showing an interest in participating in CDM projects because of the opportunities for additional financing of projects that foster economic growth and contribute to sustainable development. In the longer term, developing countries might have to fulfill their own targets for reducing GHG emissions, and there is a risk that under CDM, carbon sinks and biomass systems have been picked as the “low-hanging fruits” by industrialized countries, with only very expensive options remaining for developing countries to fulfill their obligations in the second commitment period. In assessing the costs of projects under CDM, it is essential to include all cost aspects, including the cost of monitoring and the transaction costs of establishing the contracts. For example, to achieve carbon sequestration in agroforestry, a large number of farmers will have to be contracted and transaction costs could become prohibitive. Monitoring emission reductions is essential, but expensive, particularly if the monitoring of all sinks in the relevant country becomes necessary to avoid carbon leakage.

6.6 Policy relevance and views of parties

In the previous sections, carbon sequestration and biomass activities were demonstrated as offering the potential to many Annex B countries to meet their Kyoto commitments, often at relatively low cost. This potential is enhanced and prices are lower when JI and CDM projects are considered. However, there is also a significant amount of uncertainty and risk surrounding carbon-sequestration and biomass activities (e.g. because of the mentioned permanence, the difficulty of measuring the sink, etc.), which has resulted in different views among parties to the UNFCCC (Metz *et al.*, 2001). The perception of some countries, such as the USA and Canada, was straightforward: their view was that existing forests and agricultural land contribute to carbon sequestration and that these should be taken into account in meeting their Kyoto targets—regardless of whether the uptake is due to natural causes or human activity. These countries proposed a comprehensive, broad-based approach, among other things, because this would best reflect the net effect on the atmosphere. They supported the inclusion of all possible activities under Article 3.4 and an inclusion of sinks in the CDM. Other countries, like the EU member countries, also recognized the large potential (Metz *et al.*, 2001), but they were more restrained in including sinks and biomass options in meeting commitments for several reasons. Firstly, as mentioned in section 6.3, the potential is significantly greater for some countries, which could lead to a very uneven distribution of benefits. Secondly, the permanence of the activities is a major concern. The additional carbon sequestration in the biosphere may diminish if, for example, the frequency and/or extent of disturbances, such as forest fires, were to change under future land-use activities and variations in climate (Cramer *et al.*, 1999). Furthermore, uncertainties due to leakage and additionality have been a major concern. While in JI projects, both issues would automatically be taken care of (through national inventories), they might be difficult to detect and avoid under CDM. Thirdly, the verification of sinks under CDM was questioned. In the end,, the countries were specifically against the inclusion of ecosystem conservation in CDM. Because of the huge potential (about 1.6 Gt C yr^{1}) of including ecosystem conservation, it could “flood” the market, even if only a portion would be brought under CDM.

The position of many developing countries (organized in the so-called “G77 & China” group) is divided. On the one hand, many take the view that Annex B countries should take the responsibility of reducing their domestic GHG emissions (without picking “low-hanging fruits”, as mentioned in the previous section). On the other, some countries, particularly those from Latin America, are open to including direct, humanitarian activities in CDM. These countries see these activities as a potential way to gain financially from CDM projects.

Various proposals have been made to bridge the polarization of views. For example, the EU proposed restricting categories under Article 3.4 during the first commitment period, but might accept changes at a later stage, after the implications have become clear (Schlamadinger & Marland, 2000; Metz *et al.*, 2001). Another proposal was made to restrict activities under Article 3.4 (so-called “discounting”), whereas there would be no cap put on ARD projects. Other suggestions were made to leave forestry-related activities out of CDM projects, but bring in similar projects via different routes (Metz *et al.*, 2001). The G77 & China group, for example, proposed accepting forest conservation and the reforestation of degraded land as an activity for adapting to climate change (for which founds are available). Another route would be to award a more prominent role to biomass as a substitute for fossil fuel and energy-intense materials. As mentioned above, biomass projects do not have the specific problems of carbon sequestration (e.g. permanence and verification).

Major progress has been made at COP 6 bis in Bonn in dealing with these different concerns. This includes agreements on exactly how countries (with the exception of the US) may include measures related to land use:

- An agreement on the definition of “forests”; and the activities “afforestation”, “reforestation” and “deforestation”. These activities will be defined on the basis of a change in land use.

- Sinks as a result of ARD activities can be fully used.

- Sinks due to forest management can be fully used, but only up to a maximum of 8.2 Mt C yr^{-1} and only up to the level of debits due to ARD (for some countries the net effect of ARD is currently negative, i.e., an extra source of carbon).

- Additional management (Art. 3.4) can be fully used to achieve the commitment; however, this is only up to an absolute amount determined for each country (e.g., 1.24 Mt C yr^{-1} for Germany). For some countries, these amounts are relatively large, whereas for others, they are rather small.

- Each country may choose to apply any or all of the activities during the first commitment period, as agreed in Article 3.4.

- Agricultural activities under Article 3.4 (e.g., cropland management) should be implemented by applying the net–net accounting approach (i.e., net emissions or removals during the commitment period minus removals in the base year, see section 3.3, above).

- The ongoing aging effect in many forests (especially in the northern hemisphere) and the CO_2 and N fertilization effect should be excluded from accounting.

- JI projects can also be used to achieve the commitment, but with the same restrictions as above.

- Only projects falling under afforestation or reforestation can be applied to developing countries (as part of CDM projects). Thus, ecosystem conservation (e.g., avoiding deforestation) is excluded. The CDM projects can only be used up to a maximum of 1% of the 1990 emissions of a particular Annex B country.

Thus, an agreement was established among the parties (with the exception of the USA) about the definitions, type and extent of activities allowed under Articles 3.3 and 3.4 and how sinks and biomass projects can be applied under JI and CDM. Despite these achievements, parties still have to work out details about the preferred approach. Furthermore, some issues remain open. This includes the development of definitions for afforestation and deforestation under CDM in the first commitment period, taking into account issues of permanence, additionality and age, as well as socio-economic and environmental impact. The Subsidiary Body for Scientific and Technological Advice (SuBSTA) has been asked to provide additional advice.

6.7 Discussion and conclusions on sink issue in general

Carbon sequestration and biomass offer the opportunity to slow down the increase in atmospheric CO_2 concentration considerably. It is possible to store up to about 1 to 2 Gt C yr^{1} in vegetation (especially trees) and soils of the terrestrial biosphere and related products. The actual sink depends mainly on the definitions, the eligible categories of land-use management chosen and whether or not sink projects are allowed under CDM. With respect to biomass, studies have shown that in the coming decades the potential for biomass production may increase up to a level equivalent to the current global energy demand. Whether large-scale biomass systems will become competitive depends on the implementation of policies, cost reduction through, for example, technological progress, and the future level of carbon prices. An efficient combination of sequestration and biomass involves first sequestering carbon in wood products and, at the end of their lifecycle, using the biomass for energy recovery.

An important factor that determines the net potential of carbon sinks and biomass as an option for climate change mitigation is whether or not JI will become successful and sinks will be allowed under CDM. In addition to the need for political decisions about these issues, success depends on the willingness of industrialized countries to finance projects in Eastern Europe or in developing countries. The costs of such projects are often limited. Furthermore, technology transfer and the consideration of local conditions can increase the acceptance of carbon sequestration and biomass projects under JI and CDM projects.

If applied properly, large-scale carbon sequestration and biomass production have various ancillary socio-economic and environmental benefits. Improved land management (as an Article 3.4 activity), for example, can contribute both to carbon sequestration and improvement of agricultural soils, leading to higher yields. Furthermore, as mentioned before, the chances of success for sink and biomass projects increase if investments are made in local communities. The environment may benefit from sequestration and biomass projects through increased interest in avoiding soil erosion and improving land-cover protection (with positive effects on biodiversity and watersheds). Because of these positive side-effects, sink and biomass projects may contribute to sustainable development.

Despite the large potential of carbon sinks and biomass as options to mitigate climate change and the side benefits, there are still difficulties that should be considered before actual implementation becomes feasible. Firstly, it could be argued that sinks and biomass projects have not only positive side-effects, but that there is also the risk of negative environmental and social side-effects. For example, large-scale afforestation could lead to negative effects on biodiversity in a region because of a decreased richness of species and the introduction of exotic species. Careful organization of a sink or biomass project could address these negative side-effects (e.g. by limiting large-scale monoculture plantations). Secondly, reliable monitoring and verification systems are needed. Although not yet completely developed, these systems might prove to be less difficult to establish because of the progress that has been made in the development of monitoring mechanisms. Finally, sink and biomass projects are a concern to many because of relatively large uncertainties, especially if they are implemented under CDM. Issues like the permanence, leakage and additionality have been a concern. The system of monitoring, verification, and accounting should be managed in such a way as to make beneficiaries fully aware of and responsible for lower carbon results than had been projected. The recent implementation, as accepted by the parties to the UNFCCC (with exception of the USA), addresses some of these uncertainties by including measures for discounting carbon sinks in CDM, for example. Nevertheless, some issues remain unsolved (e.g. how to deal with leakage).

In summary, the implementation of activities to either sequester carbon or replace fossil fuel use requires careful analysis of economic and technological conditions along with the various local options available for carbon sequestration and biomass. Some hurdles still have to be overcome before measures can be implemented. If, however, these problems are resolved and solutions are successfully implemented, carbon sequestration and biomass production could play an important role in reducing net greenhouse gas emissions. In addition, there are a number of ancillary benefits for local communities and the environment.

Section B: Evaluating the role of carbon plantations in climate change mitigation, including land-use requirements using the IMAGE-2 model

6.8 Methodology

6.8.1 The algorithm

The methodology to assess the C sequestration potential in carbon plantations, as presented here, is a rule-based approach that is implemented on a geographical explicit -0.5° longitude x 0.5° latitude grid (Figure 6-5). The time horizon is 2000 – 2100. This facilitates the quantification of the long-term potential of carbon plantations in different parts of the world in mitigating the build-up of CO_2 in the atmosphere. We distinguish different potentials, defined according to IPCC definitions (Sathaye *et al.*, 2001). The methodology consists of three steps (Figure 6-5). The 1st step is to determine the *physical sequestration* potential of C plantations, accomplish by adding carbon plantations as a new land-cover class in IMAGE 2 (see below for a general description of the IMAGE 2 model). All carbon pools and fluxes of the potential carbon plantations (e.g. Net Primary Production – NPP and Net Ecosystem Productivity – NEP) are calculated by the IMAGE-2 terrestrial C cycle model, taking environmental (e.g. climate and atmospheric CO_2) and local conditions (e.g. soil) into consideration. In step 2, the *social potential* of plantations is determined using the restriction, “no interference with food supply and nature conservation”. In step 3, the social potential is transferred into the economic potential by linking the C sequestration to establishment and land costs. The resulting marginal abatement cost curves can be used to compare the potential of carbon plantations with other mitigation strategies using cost minimization (e.g. Van Vuuren *et al.*, 2006). The focus of this paper is on describing and analyzing steps 1 and 2 of the methodology. We will also summarize step 3 (i.e. economic potential), but refer for details on this to the companion paper by Strengers *et al.* (2007).

Step 1: The physical sequestration potential

The starting point for this step is the *potential distribution* of C plantations around the world. Six plantations types were selected on the basis of the “Top 14 Most Planted World’s Trees” (FAO, 2001; Del Lungo, 2003) to represent suitable species in different climatic zones around the world (Table 6-3). We used, for example, gum species (*Eucalyptus* spp.) for plantations in the tropical regions, and spruce (*Picea abies*) and larch (*Larix kaempferi*) for plantations in cool and boreal regions respectively. “Potential distribution” in this context refers to the *availability* and *suitability* of land. Land is assumed to be *available* when it is not assigned as protected area and no longer used for agriculture (neither cropland nor pasture). Hence, a more realistic potential is provided, given the many other land-use purposes that may expand in the (short-term) future. *Suitability* of land is driven by various environmental conditions in terms of climate and soil. All these conditions need to be fulfilled to allow a specific plantation type in a certain region. The climatic characteristics of the plantations are derived from the best matching Plant Functional Types (PFT) – classes of plant species grouped according to physiological characteristics and the sensitivity to changes in temperature and water availability (Table 6-3a).

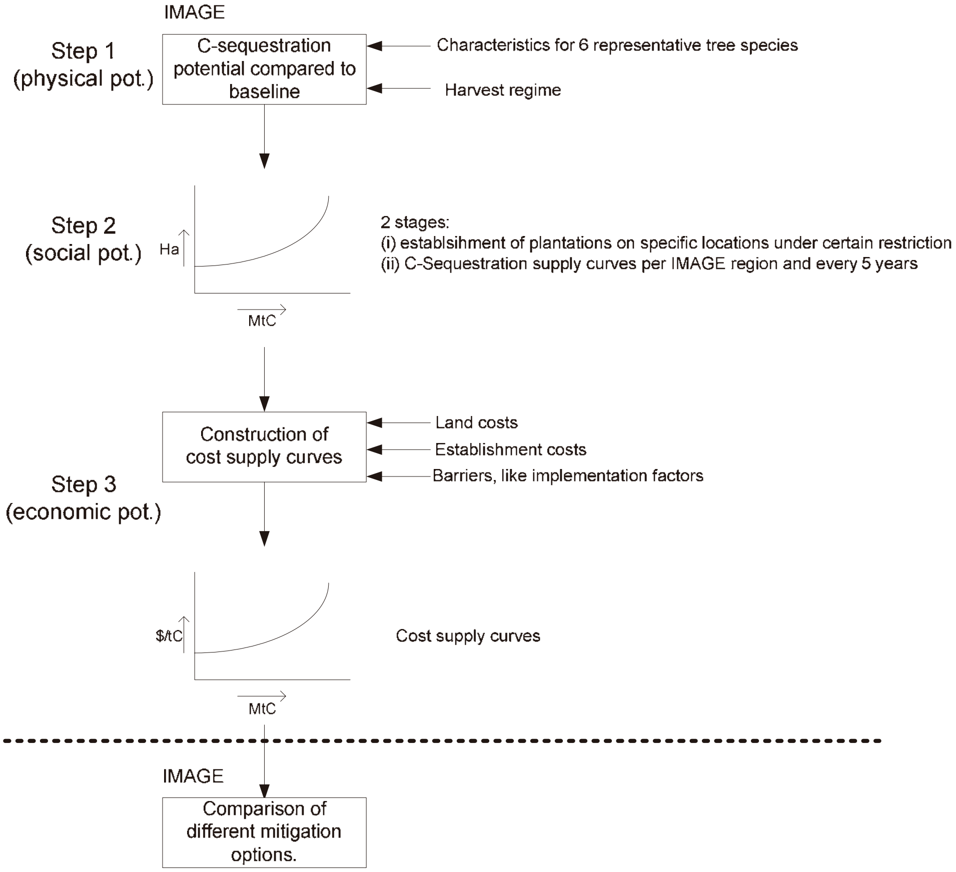


Figure 6-5 Steps to quantify sequestration potential of carbon plantations.

Table 6-3 Tree species selected for carbon plantations, and their (a) climatic and (b) carbon characteristics (b)

a)

No	Tree species		Corresponding PFT	Tcold (°C)	Moisture2	GDD5min
1	Eucalyptus camadulensis	River red gum	Tropical deciduous trees	>15.5	0.45 to 0.8	
2	Eucalyptus grandis	Rose gum	Tropical evergreen trees	>15.5	0.8 to 1.0	
3	Pinus radiate	Radiata pine	Temperate evergreen trees	>5	0.55 to 0.95	
4	Populus nigra	Black poplar	Temperate deciduous trees	-15 to 15.5	0.65 to 1.0	1200
5	Picea abies	Norway spruce	Boreal evergreen trees	-35 to –2	0.75 to 1.0	350
6	Larix kaempferi	Japanese larch	Boreal deciduous trees	< 5	0.65 to 1.0	350

[1] T_{cold} is the average temperature of the coldest month.

[2] Moisture is expressed as the ratio between actual and potential evapotranspiration Cramer & Solomon (2003). The lower end of the range may decrease due to increasing Water Use Efficiency (WUE). This is the result of increasing atmospheric CO_2 levels.

[3] $GDD5_{min}$ is the minimum degree-day sum for establishment (considering a 5°C base).

b)

No.	Corresponding land-cover types	Yield (m^3/ha.yr)	Recov. (yr)	LRL[1] (yr)	HI[2] (-)	WD[3] (Mg DM/m^3)	$FNPP_{CP}$ (Mg C/ha.yr)	AGF (-)	$CF95_{ts}$ (Eq. 2)
1	Trop. deciduous forest	12 (3–20)	8	15	0.65	0.550	18.9	2.02	1.041
2	Trop. evergreen forest	20 (10–35)	8	15	0.70	0.425	22.2	1.77	1.042
3	Warm mixed forest	14 (10–30)	15	28	0.87	0.450	11.0	1.62	1.045
4	Temp. deciduous forest	16 (8–28)	18	25	0.83	0.350	11.8	1.77	1.022
5	Cool mixed forest	11 (4–20)	30	60	0.87	0.400	8.2	1.49	1.00
6	Boreal forest	7 (4–12)	25	60	0.87	0.490	5.6	1.11	1.00

[1] Likely Rotation Length derived from FAO (2001) for both eucalyptus plantations; pine average of Nabuurs & Mohren (1993), Nilsson & Schopfhauser (1995) & Del Lungo (2003); poplar based on Nabuurs & Mohren (1993) & Del Lungo (2003); spruce based on Nilsson & Schopfhauser (1995) and larch derived from yield tables (e.g. Cannell, 1982; Schober, 1975), using the moment that growth rates start to decline.

[2] Harvest Index-based IPCC (2004)

[3] Wood density: mainly based on IPCC; If not available, use Nabuurs & Mohren (1993); Ilic *et al.* (2000); Gracia & Sabate (2002) and NRRPC (2004).

Secondly, the best growing plantation out of these six types is determined for each grid cell by using the parameters describing the C dynamics (e.g. lifetimes, allocation fractions). These parameters of the different plantation types are linked to the parameters used for the natural land-cover type that best matches the plantation type considered (Table 6-3; Leemans *et al.,* 2002; Van Minnen *et al.,* 2006). The Net Primary Production ($NPPCP_{ts}$) rates averaged over the longest likely rotation length (LRL) of each plantation type (Equation 1) are compared. The longest LRL has been chosen to take into account the period needed to reach the maximum NPP for all possible plantation types.

Equation 1 $$NPPCP_{ts}(t) = RF(t) \cdot FNPP_{lct(ts)}(t) \cdot AGF_{ts}$$

where:

ts	Index for tree species in a carbon plantation (1,..,6)
lct(ts)	Land-cover type by which the carbon dynamics of tree species (ts) are described (Table 1b)
RF(t)	Reduction Factor (≤1) during the period towards maximum average growth in terms of NPP, i.e. the recovery time (-) (Table 1b)
$FNPP_{lct(ts)}(t)$	NPP of full-grown natural vegetation in year t if the grid cell were to be covered by land-cover type lct(ts), as computed by the IMAGE-2 C-cycle model (Mg $C.ha^{-1}.yr^{1}$)
AGF_{ts}	Additional Growth Factor of tree species ts (-), (Table 1b, Equation 2)

The additional growth factor (AGF_{ts}, Equation 2) is defined as the growth rate of a plantation – based on a literature review (Equation 3) – compared to the average growth of the natural land-cover type, corrected for historical environmental changes– $CF95_{ts}$. The latter correction factor is needed because the information taken from the literature on the NPP of plantations comprised, in general, data from around 1995. Following the rules in the Kyoto Protocol – stating that sequestration credits should only be based on "direct human activities"– the NPP data needed to be adjusted. This is because these data include a growth stimulus caused by, among other factors, increasing CO_2 concentrations (which form "indirect human activities"). The *CF95* value for each plantation type (Table 6-3) has been derived by applying the IMAGE-2 C-cycle model in order to define the growth stimulants from CO_2 and climate since 1970. Note that we correct the sequestration potential up to 2100 in a similar way:

Equation 2 $$AGF_{ts} = \frac{FNPP_{CP,ts}}{NPPI_{lct(ts)} \cdot CF95_{ts}}$$

where:

$FNPP_{CP,ts}$	Average NPP of full grown plantations (Mg $C.ha^{-1}.yr^{1}$) around 1995 (Eq. 3)
$NPPI_{lct(ts)}$	Average NPP of all grid cells in 1970 covered by land-cover type lct(ts) (Mg $C.ha^{-1}.yr^{1}$) (Van Minnen *et al.*, 2006)
$CF95_{ts}$	Correction Factor for climate-induced growth stimulants for 1970–1995(-).

$FNPP_{CP}$ has been derived from especially literature on plantation yields (Brown, 2000; FAO, 2001; Del Lungo, 2003; FAO, 2004; IPCC, 2004; and Tunctaner, 2004).

Equation 3

$$FNPP_{CP} = \frac{YLD \cdot WD \cdot \frac{1}{HI} \cdot CF \cdot LRL}{\left(\frac{AFS}{LTS} - \frac{AFB}{LTB}\right) + \left(AFS + AFB - \frac{2 \cdot AFS}{LTS} - \frac{2 \cdot AFB}{LTB}\right) \cdot \left(LRL - \frac{1}{2} \cdot \mathrm{Re\,cov}\right)}$$

where;

AFS	Allocation Fraction of Stems (=0.3)
LTS	Lifetime of stems, based on the underlying land-cover types lct(ts) (yr)
AFB	Allocation Fraction of Branches (=0.2)
LTB	Lifetime of branches, based on the underlying land-cover types lct(ts) (yr)
YLD	Yield of a plantation averaged over a rotation (m^3 Fresh Volume.ha^{-1}.yr^{1}); (Table 6-4). This information is subsequently used in Equation 3 (see also Strengers *et al.*).
WD	Wood density (Mg dry matter.m^{-3} fresh volume); see Table 1b
HI	Average harvest index or the fraction of above-ground biomass used (Table 1b) of which the remainder decomposes to humus (-)
CF	Average carbon factor or carbon content (Mg C.m^{-3} dry matter)
Recov	Recovery time or average time for a C plantation to reach maturity in terms of NPP (yr); Table 6-3b

Table 6-4 Comparison of plantation growth rates around the world (m^3.ha^{-1}.yr^{-1}).

Species	This study	I	II	III	IV	V	VI	VII	VIII
E. camaldulensis	18	15–30		6–38	15–30		4–34		
E. grandis	28	15–50	30–35 (tropics) 16–30 (rest of world)		15–50		35–50	25	
P. radiate	16	12–35	20–22	26	12–35	18–30	8–23		11–25
Poplar spp.	19		12–20	9–30			8–40		9–19
Picea abies	13			5 –21			4–12	5–8	10–15
Larix kaempferi	8			5–14			4–12		

References I IPCC (2004); II Del Lungo (2003); III Brown (2000); IV FAO (2001); V Van de Hoef & Hill (2003); VI Tunctaner (2004); VII Nilsson & Schopfhauser (1995) and VIII Nabuurs & Mohren (1993).

The last part in determining the physical potential (step 1) is to estimate the net C sequestration (CSeq) potential of the best growing plantation in a grid cell. This calculation is based on the concept of SPP (Surplus Potential Productivity), as introduced by Onigkeit *et al.* (2000). The basic philosophy is to account only for the *net* C uptake of a plantation (Equation 4). This is calculated by using emissions associated with the conversion from natural land cover into a plantation and comparing the NEP flux of a plantation with the NEP flux of the natural vegetation that would otherwise grow in the area. As such, CSeq determines the *additionality* compared to the situation of having no plantations. Note that a negative value of

CSeq corresponds to a biospheric uptake of carbon from the atmosphere. In our application, the NEP fluxes are simulated by the terrestrial C cycle model of IMAGE 2, taking into account NPP and soil respiration (see below).

Equation 4 $$CSeq = b \cdot E + \sum_{t=t_0}^{t=2100} [NEP(t) - NEP_{CP}(t)]$$

where:

CSeq	Net carbon sequestration in a grid cell in the period t_0 to 2100 (Mg $C.ha^{-1}$)
t	Year (between 2000 and 2100)
t_0	Starting year of carbon plantations in a grid cell
$NEP_{CP}(t)$	Net Ecosystem Productivity of best growing tree species in a grid cell (Mg $C.ha^{-1}.yr^{-1}$)
NEP(t)	NEP of the original vegetation according to the baseline scenario (Mg $C.ha^{-1}.yr^{-1}$)
E	C content of the natural vegetation before the conversion into a carbon plantation (Mg $C.ha^{-1}$)
b	Burn factor of the initial harvest [either 0 or 1] (-)

The variables *E* and b account for carbon emissions related to the establishment of a carbon plantation. For plantations established on abandoned agricultural land, grassland or forest land just being logged, there is no clearing needed and “b” is close to zero. When, however, an existing natural forest or woodland is converted into a carbon plantation, the original vegetation is assumed to be burnt entirely (i.e. $b = 1$), resulting in instantaneous emissions of carbon into the atmosphere. These emissions must first be compensated before a plantation is effective in mitigating the CO_2 build-up in the atmosphere.

Since management can have a considerable effect on the carbon uptake potential of plantations (Karjalainen *et al.*, 2003; Phat *et al.*, 2004), we included two possible harvest regimes. Either plantations are harvested at regular intervals or no harvest takes place at all. In the latter case, a plantation will grow to a stable level of carbon storage and a low additional C sequestration further in time in the soil. In the former case, a plantation is harvested at the moment of maximum C sequestration, (i.e. the NEP of a plantation averaged over the stand age starts to decrease), followed by re-growth. In our assessment, the harvested wood from stems and branches is used to fulfill the wood demand. Leaves, roots, and the non-harvested stems and branches enter the litter and humus carbon pools in the soil. The approach of displacing wood demand amounts to a displacement factor of 1 (assuming no leakage, i.e. no change in the wood sector).

Figure 6-6 illustrates step 1, showing the C dynamics of a *Pinus radiata* plantation on either abandoned agriculture or replacing a natural forest. In the case of establishing this plantation on abandoned agricultural land (Figure 6-6a), the NPP of both the plantation and the natural forest –that would otherwise grow in the area – increases from zero up to the maximum value within the predefined recovery period. If responses to changing atmospheric CO_2 levels and climate are excluded, the NPP values will remain constant at the maximum value. The soil respiration of both the plantation and natural forest first decline, because the carbon input from young trees is limited, whereas the decomposition rate starts at the much higher equilibrium level with respect to the previous (in this case agricultural) vegetation. After a period of decline, the respiration flux increases, since the soil carbon pools are filled up again. The respiration flux increases until it exceeds NPP. If the net carbon uptake of the carbon plantation (*NEPCP(t)*) is larger than the net uptake of the natural forest (*NEP(t)*) (i.e. more negative), the plantation is effective in slowing down the build-up of atmospheric CO_2. This is illustrated by negative values of *CSeq*. Since it is unknown in advance *when* a certain potential is actually used in a mitigation effort, we averaged the carbon sequestration over a predefined period of time expressed as $CSeq_{sup}$. As such, the $CSeq_{sup}$ over the time interval $[t_s,t_t]$ is an approximation of the average net carbon sequestration over the time interval $[t_0,t_e]$.

In the case of the establishment of a C plantation on slash and burnt natural ecosystems (Figure 6-6b), large quantities of carbon are emitted instantaneously (i.e. *E* will be large). Afterwards, *CSeq(t)* in year *t* equals $NEP_{CP}(t)$, assuming no CO_2 fertilization and other climate feedbacks (as such, the NEP of the natural vegetation is about 0). However, the year that a plantation starts to actually sequester carbon is postponed because the initial emissions have to be compensated (about 23 years for the example in Figure 5).

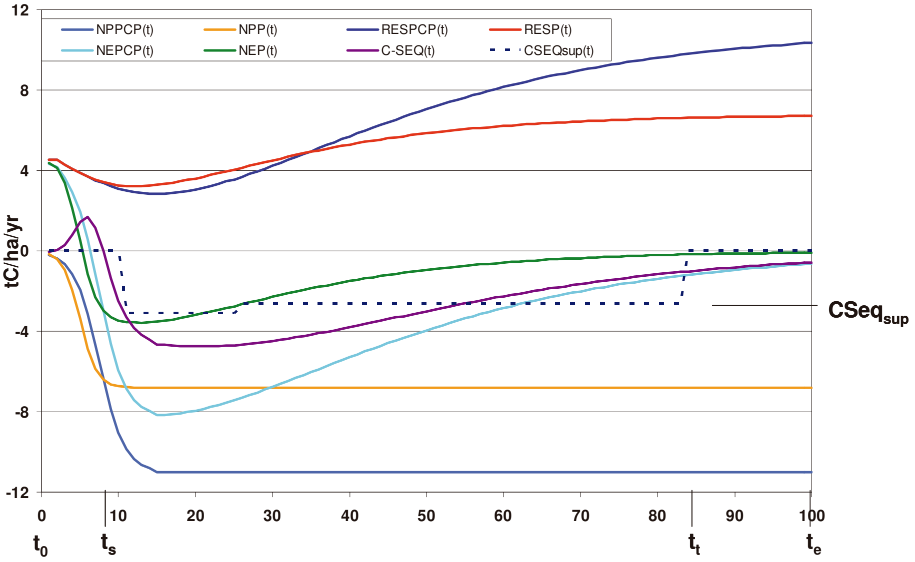
Step 2: The social sequestration potential

The social potential of the afforestation activities is estimated in two stages. Firstly, we establish plantations around the world using certain restrictions based on social acceptance. This is accomplished by assuming no interference with food supply and nature conservation. Establishing plantations on abandoned agricultural land is the only possibility. This leads to uptake potentials per grid cell (geographical explicit). Secondly, supply curves have been constructed for each IMAGE 2 region, aggregating the grided potentials for all grid cells within that region. Since it is unknown when a certain potential is actually used in a mitigation effort, and to allow for comparison with other greenhouse gas mitigation options, the carbon sequestration is averaged over a predefined period of time ($CSeq_{sup}(t)$). Thus each point in a supply curve represents the regional sum of the average annual carbon sequestration potential of a grid cell assigned to a time interval $[t_{s,}t_t]$ (Figure 6-6).

Step 3: The economic sequestration potential

The social C sequestration potential is used to determine the economic potential by linking it to costs (see Strengers *et al.*, 2007 for details). This results in Marginal Abatement Curves (MACs) or cost-supply curves dependent on geographical-explicit environmental circumstances and possible future changes in land use. In general, the

a) **permanent plantation on abandoned agricultural land;**



b) **permanent plantation on former forest area**

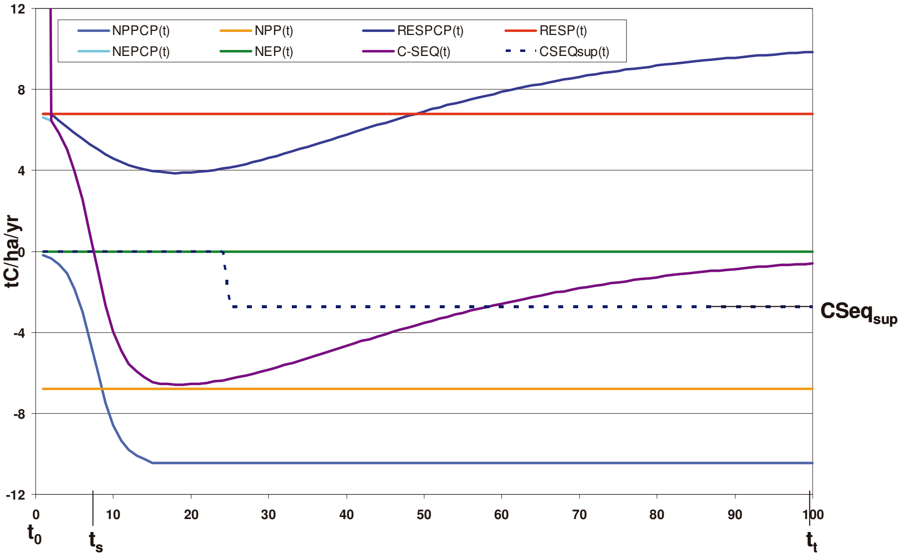


Figure 6-6 Illustrative growth curves of a *Pinus radiata* plantation.

most important cost factor in producing or conserving carbon sinks is land (Richards & Stokes, 2004). In addition, we also consider establishment costs. Other types of costs are excluded because they are either low (e.g. maintenance costs), compensated by revenues from timber, or difficult to quantify (Benítez *et al.*, 2006). Land costs are based on GTAP data (GTAP) for land values of agricultural land around the world. Establishment costs, set at 435 US$ (1995) per ha, are uniform in time and space. This assumption is supported by the survey of Sathaye *et al.* (2001). The value of 435 US$ (1995) per ha is based on analyzing variations between the regions and the ranges within the regions.

6.8.2 The IMAGE 2 model

The methodology presented was implemented in IMAGE 2 (Integrated Model to Assess the Global Environment Alcamo *et al.*, 1998; IMAGE team, 2001; MNP, 2006). This is a multi-disciplinary, integrated assessment (IA) model, designed to explore causes and effects of global environmental change. IMAGE 2 integrates different land-use demands like food, fodder, biofuels and C sequestration. IMAGE 2 is global in application and integrates regional socio-economic (i.e. 18 regions) and geographically explicit grid dimensions (i.e. 0.5^0 longitude by 0.5^0 latitude). Each grid cell is characterized by its climate, soil and land cover (natural ecosystems or agriculture). Because of the dynamic land use, the geographic explicit modeling and the global perspective, IMAGE 2 is very suitable for the presented methodology.

IMAGE 2 consists of various submodels (Figure 6-7). Drivers of the model are regional trends in wealth, demography, and technology for the period 1970 to 2100. These trends determine, for example, the demand for land resources. Changes in production of or demand for land-related products (i.e. food, fodder, biofuel, timber, and C sequestration) drive land-use changes, leading to land-use emissions of various greenhouse gases into the atmosphere. The IMAGE 2 atmospheric and ocean submodel computes changes in atmospheric composition (e.g. CO_2) and, subsequently, the climate by using the land-use and energy-related emissions and by taking oceanic and terrestrial CO_2 uptake and atmospheric chemistry into account. The climatic changes alter the distribution and productivity of ecosystems and agriculture, with both, in turn, affecting the terrestrial C dynamics.

Carbon plantations have been added as a separate land-cover class into the land-cover submodel of IMAGE 2, whereas their carbon pools and fluxes are computed by the terrestrial C cycle submodel (Klein Goldewijk *et al.*, 1994; Leemans *et al.*, 2002; Van Minnen *et al.*, 2006). The driving force of the C-cycle submodel is Net Primary Productivity (NPP), which is the photosynthetically fixed C in plants minus C losses due to plant respiration. NPP in IMAGE 2 is a function of atmospheric CO_2 concentration, climate, soil nutrient, and moisture status, biome type and the successional stage of a biome. NPP determines the Net Ecosystem Productivity (NEP) in an area, together with the heterotrophic soil respiration. NEP represents the net C flux between the atmosphere and terrestrial ecosystems. Soil respiration depends on the C stocks in the different soil compartments (i.e. litter, humus, and charcoal), their turnover rates and environmental conditions (i.e. soil water availability and temperature). All fluxes are calculated on a monthly basis, while the C pools are updated annually.

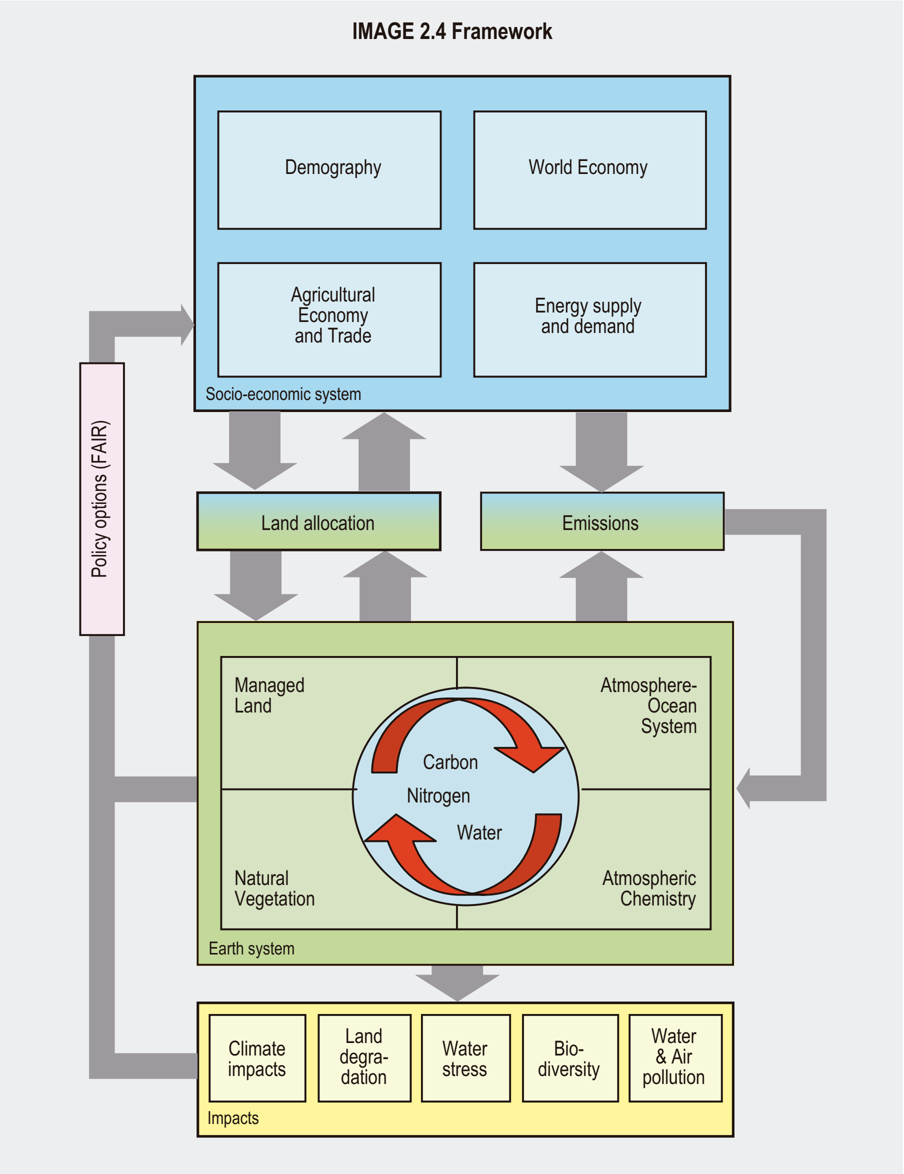


Figure 6-7 Structure of IMAGE 2.

6.8.3 Model application and experimental design

The IMAGE 2 model, along with the methodology presented here, has been applied to a number of experiments to show different sequestration potentials of C plantations up to 2100 under different baseline scenarios and management options. The experiments form variants to the implementation of the IPCC SRES A1b and B2 baseline scenarios (Nakicenovic *et al.*, 2000). The two baseline scenarios differ considerably in socio-economic and population developments (Table 6-5). In the

B2 scenario, the demands up to 2050 for goods (e.g. food, timber and biofuels) are lower than in A1b baseline. But between 2050 and 2100, the demands remain high in B2, and drop in the A1b scenario. Combined with lower yield increases in the B2 world due to lower economic development and a fragmented world (e.g. leading to less technology exchange), less agricultural land is projected as being available for C plantations in the B2 scenario than in the A1b scenario. The consequences for the atmospheric CO_2 concentration and global climate in the two scenarios are given in Table 6-5. Regionally, large temperature changes (up to 6°C) are simulated for the high latitudes, the Amazonian region, southern Africa and India.

Table 6-5 Main global characteristics of the IPCC A1b and B2 baseline scenarios (derived from IMAGE team, 2001)

Variable	Year	A1b	B2
Population (10^9 people) (in 2000: 6.1)	2020	7.6	7.7
	2050	8.7	9.4
	2100	7.1	10.4
GDP/capita (10^3 US\$.yr^{-1}) (in 2000: 5.3)	2020	8.8	7.6
	2050	24.2	13.7
	2100	86.2	27.7
Extent arable land (Mkm^2) (in 2000: 48.5)	2020	51.7	53.1
	2050	53.1	53.6
	2100	48.4	51.0
Atmospheric CO_2 concentration (ppm) (in 2000: 375)	2020	426	421
	2050	561	506
	2100	753	606
Air temperature change (°C) (in 2000: 0.6)	2020	1.0	1.0
	2050	2.0	1.9
	2100	3.4	2.9

In the first set of experiments, the *physical sequestration potential* is estimated by establishing plantations wherever the carbon sequestration is higher than in the baseline (Table 6-6), with the exception of areas used for agriculture. The variants deal with permanent plantations in the A1b scenario (Exp.1), and frequently harvested plantations in the A1b (Exp. 2) and B2 (Exp.3) baseline scenarios. In the second set of experiments we assess the *social sequestration potential* by taking into account barriers as no interference with the food supply and nature concerns. We implemented these criteria by establishing plantations on abandoned agricultural land only. Reforestation of harvested timberland is, for example, excluded, but could easily be incorporated in the methodology presented. Just as for the first set of experiments, we distinguish different types of management (Exp. 4 and 5) and baseline scenarios (Exp. 4 and 6). In this set of experiments we assume that the plantations will actually be established, allowing for an evaluation of the possible role of carbon plantations in mitigating the build-up of CO_2 in the atmosphere.

Table 6-6 Overview of simulation experiments for the IPCC A1b or B2 baseline scenarios

	Plantation management	IPCC A1b	IPCC B2
Physical potential	Permanent	Experiment 1	
	Frequent harvest	Experiment. 2	Experiment 3
Social potential	Permanent	Experiment 4	
	Frequent harvest	Experiment 5	Experiment 6

6.9 Results

Here, we present the global and regional distribution and C uptake of the plantations for the different experiments and scenarios up to 2100. Note that both the physical and social potentials of the plantations are shown.

6.9.1 Experiments 1, 2 and 3: Physical potential of carbon plantations

In these experiments carbon plantations are established wherever they can grow and wherever they are carbon-effective compared to the baseline. Under this assumption, the six plantation types are found to be effective over large areas around the world (Figure 6-8). Under the A1b baseline scenario, about 3990 and 3850 Mha (=10^{10} m^2) plantations can be established under the permanent and frequent-harvest management options, respectively up to 2100 (Table 6-7). Plantations of gum species (*Eucalyptus* spp.), for example, are projected for establishment mainly in regions that are currently covered by savanna, woodland and even some tropical forest. The potential over the next few decades is limited because, especially up to 2050, much land is needed for agricultural production (this land cannot be used because of the assumption that current and future agricultural land is to be excluded). Under the alternative B2 baseline scenario less land is projected to become available for plantations than under the A1b baseline, due to greater demand for agricultural land. The projected difference between the two management options (i.e. harvested

Table 6-7 Physical potential distribution of carbon plantations (in Mha)

Baseline	A1b Permanent			A1b Harvest			B2 Harvest		
	2030	2050	2100	2030	2050	2100	2030	2050	2100
River red gum	545	620	965	621	700	997	514	533	701
Rose gum	790	814	1310	1027	1039	1257	906	939	1157
Radiata pine	20	25	33	20	25	33	22	30	38
Black poplar	86	121	445	151	236	434	146	206	436
Norway spruce	792	845	984	778	828	855	1047	1141	1254
Japanese larch	100	158	254	128	183	272	139	195	247
Global total	2333	2583	3992	2726	3011	3848	2774	3044	3833

or permanent plantations) has two reasons. Firstly, the difference results from the assumption for permanent plantations that abandoned agricultural land is not available if the re-grown natural forest is needed at a later stage to fulfil the wood demand. Secondly, close to 2100 permanent plantations are estimated to be more widely distributed because the CO_2 emissions related to the harvest of plantations need to be compensated before harvested plantations become an effective C sink.

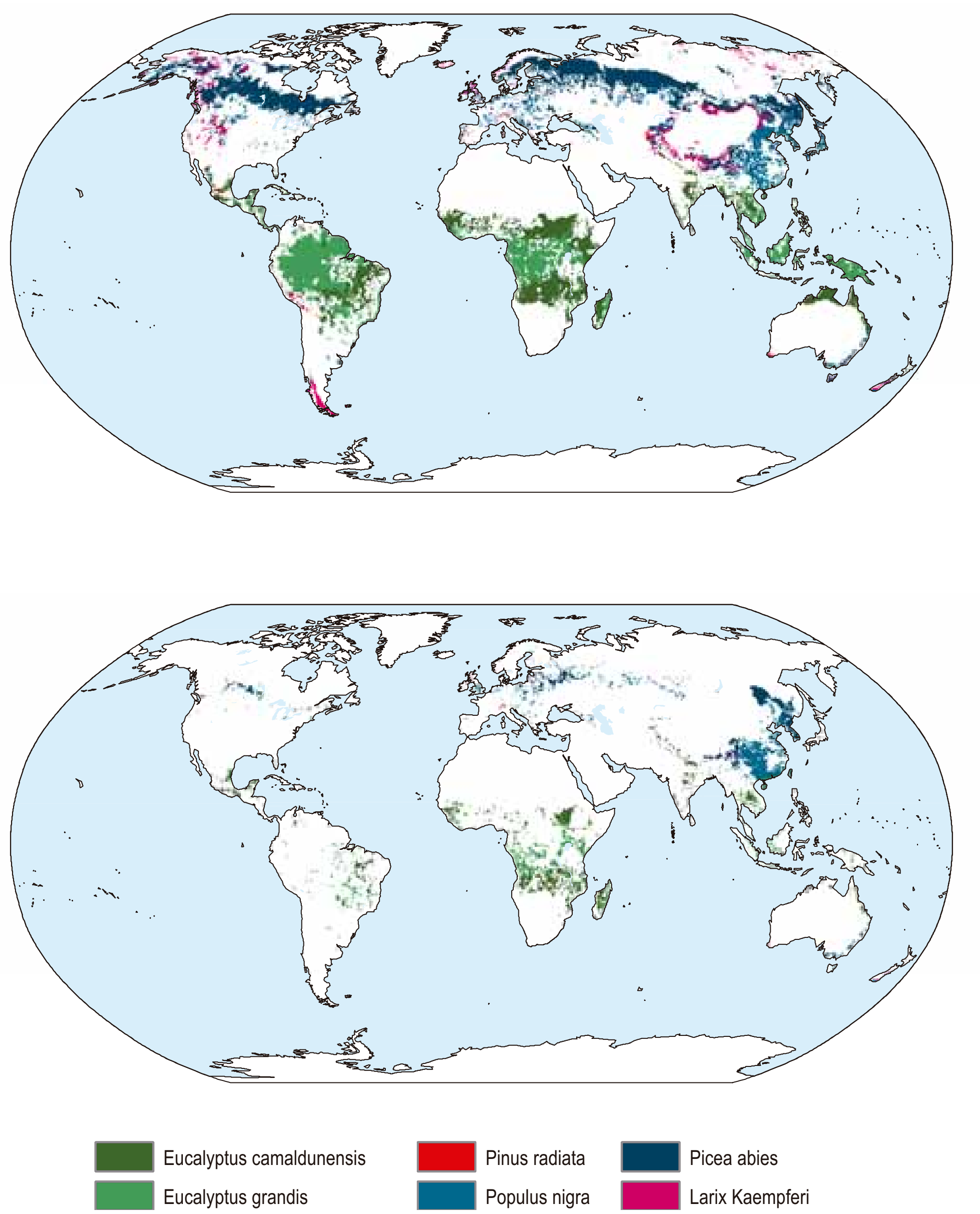
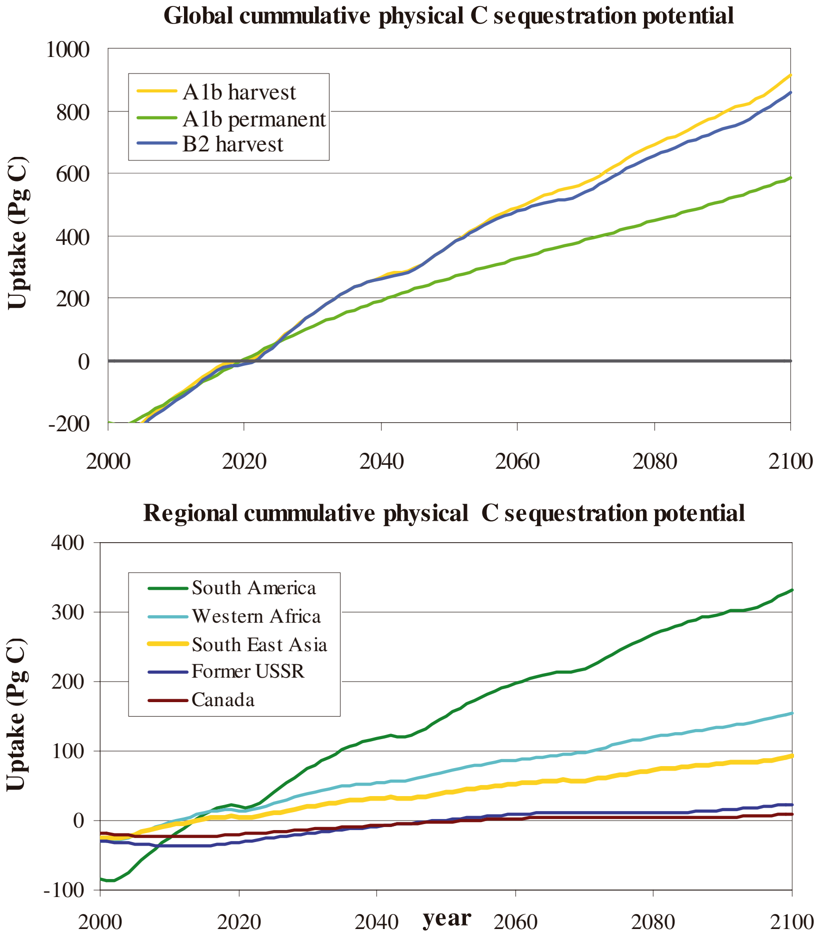


Figure 6-8 Physical (top) and social (bottom) potential distribution of permanent carbon plantations in 2100 using the A1b scenario.

The projected cumulative physical C sequestration of plantations in the A1b scenario is 583 Pg C and 913 Pg C up to 2100 for the permanent and harvest options, respectively (Figure 6-9). Under the B2 baseline scenario, the cumulative potential is estimated to be 858 Pg C, considering frequent harvests (i.e. 6% less compared to A1b). These uptake rates equal about 37% and 58% of the projected overall CO_2 energy and industry emissions in the A1b scenario for the permanent and harvest options, respectively. Under the B2 baseline, the estimated uptake is even 67% of the energy and industry emissions. Hence, the projected long-term physical potential of carbon plantations for slowing down the atmospheric CO_2 increase is large. However, it will take more than 20 years to compensate for carbon emissions related to the establishment of the plantations. The projected physical potential up to 2020 is negligible where the cumulative potential up to 2030 is about 100–150 Pg C (Figure 6-9).


Global cummulative physical C sequestration potential

Regional cummulative physical C sequestration potential

Figure 6-9 Cumulative physical global (top) and regional (bottom) C sequestration potential (CSeq). Regional figure illustrates the trend in the A1b harvest experiment (in Pg C).

The two management options show a different trend, especially beyond 2050 (Figure 6-9). This is caused by a decreasing sequestration rate for the permanent plantations, whereas the uptake potential remains high under frequent harvests. This difference is induced by the C sequestration of plantations decreasing with age. The age increases in permanent plantations but remains low in the frequent harvest case. This difference is projected specifically for plantations in South America and Africa.

Geographically speaking, the highest physical sequestration rates have been projected for plantations in tropical regions like South America and Africa, dominated by the two Eucalyptus plantation types (Figure 6-9b). The projected sequestration potential is relatively low in high latitudes, because of low growth rates. In various parts of Canada and Russia, the net cumulative carbon sequestration even remains negative for about 50 years.

6.9.2 Experiments 4, 5 and 6: Social potential of C plantations

We assessed the social sequestration potential of C plantations up to 2100 using wood supply and nature conservation as main constraints in addition to the food security criterion. These constraints have been implemented by estimating the potential on abandoned agricultural land only. Assuming permanent plantations, 181 and 831 Ma are projected in the A1b scenario to be established around the world up to 2050 and 2100, respectively (Table 6-8). With respect to harvest, the area available in 2100 for C plantations is projected to be 1014 and 695 Mha under the A1b and B2 baseline scenarios, respectively. The difference between the baseline scenarios is caused by a larger land abandonment under the A1b baseline scenario than under the B2 baseline.

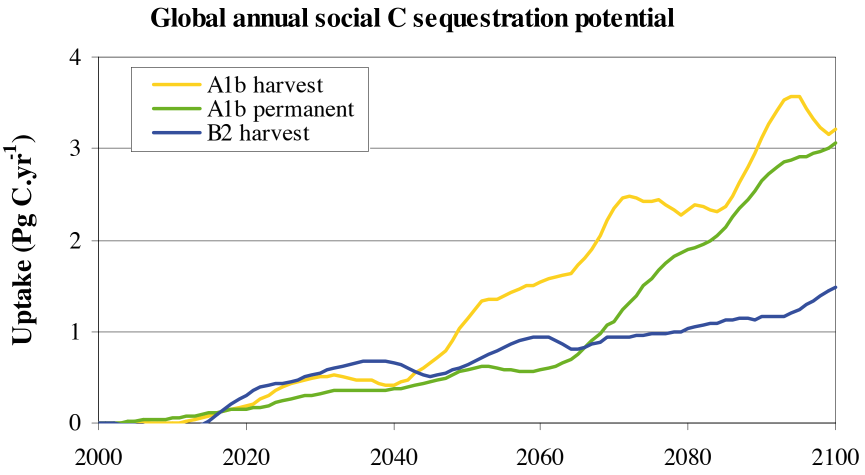
Table 6-8 Social potential distribution of carbon plantations with establishment on abandoned agricultural land only (in Mha)

Baseline	A1b Permanent			A1b Harvest			B2 Harvest		
	2030	2050	2100	2030	2050	2100	2030	2050	2100
River red gum	31	75	317	33	83	332	30	37	158
Rose gum	20	26	230	30	41	256	21	34	108
Radiata pine	2	2	3	2	2	3	2	2	3
Black poplar	16	24	192	23	83	219	31	84	163
Norway spruce	31	48	75	128	164	181	119	203	234
Japanese larch	4	5	14	11	16	22	15	23	29
Global total	105	181	831	228	390	1014	218	383	695
USA	0.9	0.7	2.7	5.0	3.8	2.8	18.4	51.3	70.5
Latin America	40.0	35.0	66.5	76.3	57.5	74.9	35.5	53.8	34.1
Africa	6.4	50.1	327.0	10.5	79.1	365.2	0.4	1.5	143.0
Europe	0.3	1.0	20.3	4.3	14.3	25.5	17.4	36.0	32.5
FSU	13.7	19.7	47.1	48.7	60.4	60.7	83.3	110.2	117.8
China	0.3	18.2	196.2	3.0	84.0	288.5	1.6	22.9	143.7

The difference between the two management options is caused by the assumption for permanent plantations that abandoned agricultural land is not available if the re-grown natural forest is needed at a later stage to fulfill the wood demand. For frequently harvested plantations, the timber from the plantations is used to fulfill the wood demand, reducing the pressure on existing forests. Similar to the physical potential, the difference between the management options is projected to decrease near to 2100 because the CO_2 emissions related to the harvest need to be compensated before the plantations become an effective C sink. As a consequence, fewer harvested plantations will be established.

The majority of the plantations is projected in all the experiments to be established after 2050, because land only becomes available then due to decreasing population and increasing efficiency. The projected cumulative global social C sequestration potential remains low in the coming decades (Figure 6-10), and, up to 2050, reaches 12–17 Pg C for the different baselines and harvest regimes (Table 6-9). Under the A1b scenario the potential increases up to 93 and 133 Pg C in 2100 for permanent and harvested plantations, respectively (Figure 6-10, Table 6-9). This is 5 –7% of the projected cumulative emissions up to 2100 coming from the energy and industry sector (i.e. about 1740 Pg C). The potential uptake up to 2100 under the B2 scenario is 68 Pg C, implying 5% of the energy and industry emissions (i.e. 1272 Pg C). The net C sequestration potential can be higher under a frequent harvest regime due to a higher area-based uptake and the broader distribution. Comparing the 2 baseline scenarios, the projected global sequestration of carbon plantations in 2100 is 95% higher under the A1b scenario than in the B2 baseline (Table 6-9), mainly due to the higher establishment rates.

Geographically speaking, most plantations are projected for establishment in tropical regions (Figure 6-8, Table 6-8). The consequences for the C sequestration are that under the A1b baseline scenario, 40–50% of the global potential can be sequestered in plantations in Africa, 10–20%, in China, 10% in Latin America, and 10% in Oceania (Table 6-9). Although a considerable amount of abandoned agricultural land is projected for Europe, Canada and the FSU as well, the effectiveness of establishing C plantations here is projected as being limited. For example, 6% of the global potential area can be established in the FSU up to 2100, sequestering only 4% of the global potential.



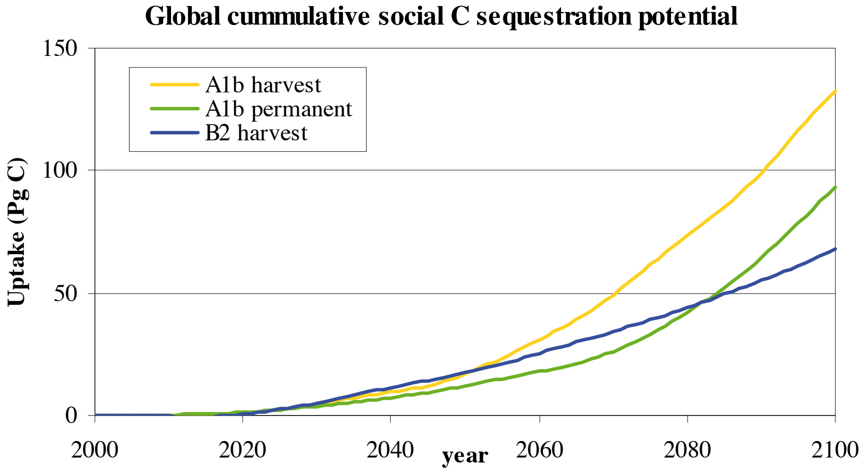


Figure 6-10 **Social C sequestration potential (CSeq) on abandoned agricultural land; top~ annual (Pg C/ yr), bottom ~ cumulative (Pg C).**

With respect to the social potential, evaluating the effectiveness of carbon plantations in slowing down the build-up of CO_2 in the atmosphere shows that the concentration in 2100 under the A1b scenario can be reduced from 752 to 713 ppm (-39 ppm) when planting permanent carbon plantations, whereas it reaches 700 ppm (-52ppm) assuming frequently harvested plantations (Table 6-9). The two management options differ because of the broader distribution of carbon plantations when planting frequently harvested plantations and because of the additional C that will be stored in the soil compartment. The lower social sequestration potential projected under the B2 baseline scenario results, obviously, in a lower effectiveness. Assuming frequently harvested carbon plantations, we project a CO_2 concentration of 579 ppm in 2100, which is 27 ppm less than in the baseline.

Table 6-9 Implications of establishing carbon plantations on abandoned agricultural land

Indicator	**2050**			**2100**		
	A1b perm.	**A1b harvest**	**B2 harvest**	**A1b perm.**	**A1b harvest**	**B2 harvest**
Baseline atmos. CO_2 concentration (ppm)	561	561	506	753	753	606
Change in CO_2 concentration, compared to baseline (ppm)	-5	-6	-8	-39	-52	-27
Cumulative social C sequestration potential in C plantations on abandoned agricultural land only (Pg C)						
Global potential	12	17	17	93	133	68
USA	*0.1*	*0.3*	*1.7*	*0.3*	*0.7*	*7.5*
Latin America	*3.9*	*4.7*	*3.8*	*9.8*	*14.6*	*9.5*
Africa	*2.8*	*3.5*	*0.1*	*47.9*	*57.1*	*8.1*
Europe	*0.1*	*0.4*	*1.5*	*0.7*	*1.5*	*3.6*
FSU	*0.6*	*1.9*	*3.9*	*3.4*	*5.4*	*7.7*
China	*0.1*	*0.8*	*0.2*	*10.3*	*25.9*	*10.3*

6.10 Discussion

6.10.1 The carbon sequestration potential in comparison with other studies

Here I have presented a methodology to assess the global and regional sequestering potential of carbon plantations established after 2000. Physically, the projections demonstrate that carbon plantations can be effective in large parts of the world with a cumulative sequestering potential of 913 Pg C up to 2100. In the A1b baseline scenario this equals 52% of the total cumulative CO_2 emissions from energy and industry from 2000 to 2100. In the B2 scenarios it is even 67%. The social sequestration potential is much lower but still considerable. The annual average global potential is projected at 0.1 – 0.2 Pg C yr^1 up to 2050 , and 0.68–1.3 Pg C yr^1 up to 2100 (Table 6-9). In 2100 this leads to a 27–52 ppm smaller increase in the atmospheric CO_2 concentration and compensates for 5–7% of the total energy-related CO_2 emissions. The sequestration potential is likely to considerably increase beyond 2100, because many plantations are projected to be established only close to the end of the 21st century. This holds especially for regions where large areas of arable land are expected to become available, such as China.

The social sequestration potential of the plantations projected up to 2050 is found in the literature at the low end of ranges, whereas values for the coming 100 years are more in line (Table 6-10). Regionally, the most effective plantations are located in tropical regions, whereas the C sequestration in high latitudinal plantations is limited

Table 6-10 Comparison of existing C sequestration projections

Reference	Total C sequestration (Pg C.yr^{-1})	Areal C sequestration (Mg C.ha^{-1}yr^{-1})	Period	Remarks
Global studies				
This study (social potential)	0.12 – 0.17 0.68 - 1.33	0.9 - 1.3 0.8 - 1.3	2000-2050 2000-2100	Considering sequestration on abandoned agricultural land only
Cannell	0.2 – 1		2000-2050	Conservative potential for 50-year period
Nilsson & Schopfhauser	avg 1.04		1995-2095	
Watson *et al.*	0.2-0.58		2008-2012	
Vrolijk *et al.*	0.15-0.8		2008-2012	
Lal	0.6-1.2		2000-2050	Only in degraded land soils. Total potential is 30-60 Pg C.
Richards & Stokes	0.3-2.9	0.8-1.6	2000-2075	Large variation due to different assumptions on yields
Regional studies (Compared to Table 6-8)				
Cannell	0.02-0.05			Europe, a 100-year period
EEA	0.006 0.01 0.02		2010 2020 2030	EU25 countries
Smith *et al.*	0.05 0.12		2100	EU15. only soils Wider Europe (excl. Russia). only soils
UNFCCC		0.3-0.6		European forests during 2008-2012
Krankina *et al.*		0.35		North-west Russia
Chen *et al.*		1.4	1999-2000	Canada
Liski *et al.*	0.88 0.11 0.43 0.10 0.17	0.3 0.52 0.48 0.25 0.56	Current	Sink of all boreal and temperate forests All European forests All Russian forests All Canadian forests All US forests
Silver *et al.*		2-3.5		Average sequestration of tropical forests during an 80-year period
Richards & Stokes		0.6-1 0.5-11 1.4-2.3 7.5-7.7		Only above-ground sequestration. soil decomposition fluxes excluded Canada USA (many studies summarized) Western Europe Australia

(Table 6-9). This is in line with the findings of Masera *et al.* (2003) and Cannell (2003). Many other estimates are especially useful in a comparison with our area-based potentials, because the studies often focus on the C sequestration potential in existing forests (Table 6-10). For example, the projected social C sequestration potential of tropical plantations of Latin America and Africa (1.6–1.9 Mg C.ha^{-1}yr^{-1} for 2000–2100), is found at the low end of the range given by Silver *et al.* (2000). Our projections for Europe up to 2100 – between 0.3 and 1.1 Mg C.ha^{-1} yr^{-1} – are well in line with the projected area-based uptake of 0.52 Mg C.ha^{-1} yr^{-1} given by Liski *et al.* (2000).

Despite the estimated considerable C sequestration potential up to 2100, the projected uptake potential for the coming decades is limited (Figure 6-10). It can take about 20 years to compensate for the emissions related to the establishment of the plantations. Moreover, not much agricultural land will likely be abandoned in coming decades due to the current and projected agricultural pressure. The limited potential in coming decades is in line with findings of Marland & Schlamadinger (1999), who showed that the sequestration potential in forests established since 1990 is mainly relevant in the long term. As such, we do not confirm the suggestion of Kirschbaum (2003) that plantations may help to buy some time in initiating emission reductions already in the next few decades.

The limited role of plantations in the coming decades might be caused by our assumptions that C plantations can only be established after 2000. Various other studies report afforestation activities in different locations around the world, even before 2000. Brown (2000) and FAO (2001), for example, reported that globally 124 Mha and 187 Mha forest plantations had been established up to 1995 and 2000, respectively. More than 90% of these plantations have been established in 30 countries only, mainly in such Asian countries as China (45 Mha), India (32Mha), and Japan (11 Mha). Furthermore, various studies report existing afforestation activities, but seldom account for deforestation in the same region (the so-called leakage effect). This has also been shown by, for example, Houghton (2003), in quantifying the annual afforestation rate in the tropics to 2.6 Mha.yr^{1} throughout the 1980s, but at the same time a deforestation of 15.4 Ma.yr^{1}. In the methodology presented, leakage is not possible because C plantations are only established on land that is available for the entire simulation period (i.e. up to 2100). Finally, our projections are lower than in other studies that account for the C sequestration in forests planted for various other reasons (e.g. recreation, agroforestry, and soil restoration). For India, for example, a negligible afforestation potential is projected up to 2030, because of the large pressure on the land for food production. Nevertheless, Ravindranath & Somashekhar (1995) reported an afforestation rate of India of 1.6 Mha.yr^{1}, mainly for agroforestry purposes. Again, these afforestation rates are partly counterbalanced by deforestation activities in India (Sathaye *et al.*, 1999; Houghton, 2003).

6.10.2 The methodology in relation to conventions and protocols

The methodology presented is aimed at quantifying the sequestration potential of carbon plantations around the world, considering the requirements mentioned in different conventions and protocols. The UN Framework Convention on Climate Change (UNFCCC, 1993) and its underlying Kyoto Protocol, which opened the possibility for developed countries to use afforestation programmes in achieving their reduction commitments, clearly stress that C plantations are only effective in the long term if:

- they are *additional* to a baseline.
- all C fluxes are considered (i.e. *full C accounting).*
- they are *permanent*. If not, a carbon plantation has little value in terms of actually reducing the concentration of GHG in the atmosphere, since carbon sequestered over various years will return to the atmosphere.
- the credited C sequestration in one region is not to be compensated by C losses elsewhere (= no *leakage*) Metz *et al.*, 2001).
- the C sequestration in plantations exclude "indirect human influences" in terms of, for example, climate and CO_2 change.

(see also Schlamadinger & Marland, 1998; Watson *et al.*, 2000; IPCC, 2004).

The *additionality* issue has been taken into account in the methodology presented by considering the sequestration potential of both plantations and natural ecosystems. Furthermore, the methodology considers *all C fluxes* by keeping track of fluxes in both vegetation and soil, plus the carbon losses due to the establishment of the plantations. The *permanency* concern is taken into account by comparing the C plantation option with various other land-use options. Alternative land-use options pose a main threat to the permanency of a carbon plantation, especially in the long term (e.g. when the demand for agricultural land fluctuates or prices of land-use products change). Since permanency is more certain if plantations are established in areas that are not used for food, fodder and timber production, areas needed for agriculture or wood up to 2100 have been excluded in the all experiments. As mentioned earlier, leakage is not possible in the methodology presented because plantations are only establish on land that is available for the entire simulation period (i.e. up to 2100). Finally, the methodology accounts only for carbon sequestered *directly* by the plantations, corrected for climate change and CO_2 fertilization (i.e. indirect human influences). This has been done both for the historical uptake – where 1995 growth rates have been corrected for observed changes in CO_2 and climate (see Equation 2) – as well as the projected future (reducing the projected social potential in the supply curves for climate and CO_2 changes in the baseline).

6.10.3 The effectiveness of carbon plantations in a broader environmental context

The effectiveness of harvesting plantations and using the biomass to displace fossil fuels and/or timber, compared to having carbon stored in a permanent plantation, depends to a great extent on the displacement factor (i.e. the extent to which wood from carbon plantations can be effectively used to replace fossil fuels) (Stinson & Freenman, 2001). Here, a displacement factor of “one” is assumed. Theoretically this can be achieved if fossil fuels are displaced by harvested wood (Cannell, 2003; Deckmyn *et al.*, 2004). However, if the displacement factor is (much) smaller than “one”, the environmental effectiveness of harvested plantations decreases sharply. Likewise, establishing carbon plantations is, in general, less effective than avoiding deforestation (especially in tropical regions, Fearnside, 2001; Sathaye *et al.*, 2001). This, however, is associated with various social difficulties, and avoiding deforestation in one region may be counterbalanced by additional deforestation elsewhere.

The effectiveness of carbon plantations in especially high latitudes is questioned because of the effect on different biophysical processes (i.e. changed radiation balance) that may counterbalance the additional biochemical C sequestration (Betts, 2000; Marland *et al.*, 2003; Schaeffer *et al.*, 2006). On the basis of the albedo effect and the projected low net sequestration potential for high latitudinal plantations (i.e., in parts of Canada and Russia the net C sequestration even remains negative for about 50 years), the establishment of carbon plantations in high latitudes is only favorable if the objective to sequester carbon is combined with other environmental considerations. For example, under certain conditions, plantations may also contribute to water protection and soil erosion control (Cannell, 2003; Jackson *et al.*, 2005).

An environmental constraint often mentioned for large-scale C plantations is the availability of water and nitrogen (Schlesinger, 2000; Hungate *et al.*, 2003; Jackson *et al.*, 2005). Also in the methodology presented, the high growth rates of the carbon plantations (compared to natural forests) rely on a high level of management, including nitrogen fertilization for plantations situated on poor or degraded soils. The additional use of water and fertilizer should indeed be a concern in the planning and management of the plantation, especially because a (higher) fertilizer use could imply additional emissions of N_2O, which were neither accounted for in our study, nor in most other studies. Likewise, afforestation activities have recently also been questioned in the context of possible additional methane emissions from trees – the second-most important greenhouse gas (Keppler *et al.*, 2006). Although this issue is currently still under scientific debate, the effectiveness of afforestation programs would be reduced by a maximum of 10%. This has been confirmed by others (see, for example, Kirschbaum *et al.*, 2006 and www.realclimate.org/index.php?p=236 for more detailed discussion).

6.11 Conclusions

We have presented a rule-based methodology to quantify the long-term physical and social sequestration potential of carbon plantations up to the end of the 21st century and their effectiveness in slowing down the increase in atmospheric CO_2. Applying the methodology, we conclude that projected potentials differ considerably for different experiments, regions and management options. For example, we projected a nearly 100% difference in the sequestration potential up to 2100 between two baseline scenarios, showing the effect of uncertainties in future land use. Nevertheless, in all cases the C sequestration potential can be substantial. Even under a conservative set of assumptions, the cumulative sequestration potential up to 2100 can compensate for 5–7% of the total energy-related CO_2 emissions. But the sequestration potential is substantial only in the long term. The potential for the coming decades is limited due to the limited amount of available land and the long period needed to compensate for emissions related to the establishment of the plantations. Geographically speaking, plantations in tropical regions are most effective. The C sequestration potential of plantations in high latitudes is low and because of biophysical feedbacks on the climate system, its overall effectiveness here can be questioned. The establishment of plantations in these regions is only favorable if the objective to sequester carbon is combined with other environmental considerations.

Finally, our analysis showed that C sequestration in plantations may be substantial and thus can help to slow down the future increase in atmospheric CO_2. But C plantations do not represent the ultimate solution to the problem of establishing a stabilization of the atmospheric CO_2 concentration. They should form part of a broader package of options, with clear measures for also reducing energy emissions.

Chapter 7

Conclusions

7. Conclusions

7.1. Introduction

In this thesis I have assessed the response of the terrestrial biosphere to environmental and land-use changes, and the consequences for the global and regional carbon (C) cycle. I determined, for example, crucial processes and important uncertainties. In comparison with other assessments of the C cycle, an integrated approach is used that includes socio-economic (i.e. land-use) and natural (biogeographical and biogeochemical processes) dimensions, including their interactions and feedbacks. Furthermore, the changes in land use included deforestation for cropland and pasture expansion, timber, and reforestation. Finally, I have presented global and regional results for the past three centuries and the robustness of future emission scenarios (up to 2100) using a sensitivity analysis.

The backbone of the thesis is the terrestrial C cycle model of IMAGE 2. The model is described, and results are shown for the different applications under multiple socio-economic and environmental conditions. Results were also compared with observed trends, and the results of simpler and more complex models. On the basis of the results of these analyses, I provide answers to the five research questions introduced in chapter 1.

7.2. Research questions

1. **What are the main processes that determine the role of the terrestrial biosphere in the C cycle on global and regional scales?**

In this thesis I have shown the terrestrial biosphere to play a crucial role in the global C cycle on time scales ranging from months/seasons to centuries. The biosphere stores large quantities of carbon and exchanges considerable amounts with the atmosphere at rapid rates. On longer time scales, the ocean exchange becomes more predominant. Oceans store by far the largest amount of C, but since the C is relatively inert, it will be less relevant for the changes in the C cycle over the coming decades.

The role of the biosphere in the global C cycle is determined by many biogeochemical, biophysical, ecological and anthropogenic (i.e. land-use) processes. Important biogeochemical processes are net primary production (NPP), soil respiration and disturbances. All these processes interact and are affected by changing environmental conditions. The relevance of the individual processes in the C cycle also depends on the temporal and spatial scales considered. When considering biogeochemical feedbacks, for example, a robust finding of many studies -including this thesis- was that the most important process globally is CO_2 fertilization (i.e. the physiological response to increasing CO_2 levels in the atmosphere). Ignoring this effect has larger consequences for C fluxes and pools than uncertainties in future land use do. Regionally, there are differences: CO_2 fertilization and the climate effect on soil respiration are the most relevant in tropical regions, whereas in boreal regions, the NPP response to temperature, along with CO_2 fertilization, determine the C pools and fluxes. Likewise, land-use changes related to crop and pasture expansion currently have major impacts on the C cycle in tropical regions, whereas wood harvest is especially relevant for the C cycle in temperate regions.

The understanding of the terrestrial C cycle has significantly improved in recent decades thanks to a combination of laboratory and field experiments, satellite observations and modeling exercises. As a result, the present-day ranges in estimated global C pools and fluxes have decreased. Estimates of the global NPP in the 1980s and 1990s, for example, ranged from 45 to 68 Pg C.yr^{1}. More recent studies show ranges from 55 to 63 Pg C.yr^{1} (while this study provides a range of 58 to 61 Pg C.yr^{1}). Likewise, projections on the future role of the biosphere have become more consistent. Many modeling studies have shown the terrestrial C storage in the next decade to increase, followed by a decrease towards the end of the 21st century. However, regionally – especially in tropical regions – the differences among studies are still considerable. This is caused by using different measurement methods, definitions, and time periods.

2. What are the consequences of past and future changes in climate and land use on the regional and global terrestrial C cycle?

This thesis provides new estimates on past, current, and future C fluxes – both global and regional – from land use and natural ecosystems. The historical estimates are based on an analysis using both IMAGE 2 (version 2.4) and the HYDE dataset of historical land-use reconstruction. For the projections, the most sensitive parameters of the IMAGE-2 model (version 2.3) were identified using a sensitivity analysis.

On the basis of these simulations, I conclude that for the past centuries, land use has had a more important role in the global and regional C cycle than natural processes. Net, land-use changes and the natural processes emitted 35 Pg C to the atmosphere throughout the 1700-2000 period. If land use had remained constant at its distribution in 1700, the estimated terrestrial C storage would have increased by 142 Pg C. This overall difference in terrestrial C storage of 177 Pg C is more than half the historical fossil fuel-related emissions of 308 Pg C. Up to 1900 land-use emissions were even estimated to be dominant over energy emissions. In past decades the relative importance of land use has decreased due to lower land-use emissions (e.g. 1.3 Pg C yr^{1} for the 1990s) and accelerating environmental change (e.g. climate, CO_2, and nitrogen deposition), which is rapidly altering the terrestrial ecosystems and their C fluxes.

The historical roles of land use and natural processes have varied geographically. In Europe and especially the USA, land-use change played an important role at the end of 19th, and early 20th century, resulting in considerable C emissions. This trend changed around 1950, because agricultural abandonment led to afforestation. Nowadays, both the land use and natural fluxes in these regions are a considerably lower than energy- and industry-related emissions. Most tropical regions are estimated to have been about C-neutral prior to 1950. The accelerated deforestation since 1950 has resulted in considerable loss of natural ecosystems and associated CO_2 emissions and lower natural C uptake rates. Thus these regions have now become major C sources. Although energy and industry-related emissions are currently also increasing in many tropical regions, in several countries they are generally still lower than the land-use emissions. Avoiding future land-use changes in these regions would effectively limit further increase of atmospheric CO_2. However, given the importance of the energy sector, climate policies that focus solely on slowing down deforestation or enhancing afforestation will not be sufficient to mitigate all climate change.

Land use and natural processes are also projected as being important for the future global and regional C cycle. The historically important (sometimes even dominant) role of land use in the terrestrial C cycle is projected to decrease. This is because the biosphere C uptake changes more than the land-use emissions due to substantial responses to the changes in climate and CO_2. Global land-use emissions are, however, projected to increase in all scenarios up to about 2050 (with a maximum of 2.7 Pg C yr^{1} in the IPCC SRES A1b baseline scenario). Beyond 2050, the emissions vary among the scenarios, from a continuous increase in the A2 scenario (up to 3.9 Pg C yr^{1} in 2100) to a decrease in the B1 scenario (down to 0.8 Pg C yr^{1}). The global NPP is projected to increase up to 73-77 Pg C yr^{1} in 2050 and 77-88 Pg C yr^{1} in 2100. With regard to the net biosphere uptake, a robust finding from different baseline scenarios (and in line with other studies) is the projected increase up to the middle of the 21st century, followed by a stabilization or decrease. Overall, the terrestrial biosphere is projected to sequester 22- 46% of the total C fossil fuel and land-use emissions during the 21st century.

Given the substantial role that land use and natural processes play in the historical and current terrestrial C cycle, as well as the geographical and temporal variation, I conclude that there is a need for an integrated approach to energy use, the natural ecosystems and land use, when simulating the behavior of the C cycle.

3. What are key uncertainties in determining the response of the terrestrial C cycle to climate change?

This thesis reflects the assessment of different uncertainties in ecosystem processes and land use and also a quantification of the effects of these uncertainties on the global and regional C cycle.

Experiments assuming different ecosystem responses to climate change and land use, and different baseline scenarios, show that these uncertainties have large consequences for the C cycle. It can, for example, not be ruled out that the current terrestrial C sink will turn this century into a C source. And uncertainties in future land-use change lead further to close to 100% difference in sequestration potentials of carbon plantations. When comparing the different elements of the global C cycle, uncertainties in ecosystem processes in response to climate change are shown to have larger consequences than uncertainties in future land use; these consequences are only slightly smaller than impacts of uncertainties in socio-economic drivers. Furthermore, the combined experiments show the overall uncertainty not be just the sum of the individual uncertainties. Interactions and non-linear behavior in the ecosystem response to climate change increase uncertainties.

What processes determine the large uncertainty in the ecosystem response to climate change and land use? I showed that the relevance of the processes depends on the scale considered. Globally, the most important source of uncertainty is the CO_2 fertilization effect. Regional climate, land use, CO_2 fertilization and soil respiration are most important in tropical regions. The C cycle in high latitudes has been mainly determined by CO_2 fertilization, temperature feedbacks, and the migration ability of species in response to climate change.

Unfortunately, the future strength of the CO_2 fertilization effect is still unknown, especially in natural vegetation. Different experiments and models use different assumptions and how to robustly scale the CO_2 fertilization effect to continental scales is still controversial. Developing robust parameterizations for this process should therefore be a key issue in climate change research.

Overall, I have shown that the response of the C cycle to climate and land-use change depends highly on the selected processes and their underlying parameterization. Some processes are more important than others –depending on the scale – and have multiple interactions. But all processes contribute substantially to the apparent uncertainty in the C cycle. This uncertainty should be considered in climate change mitigation studies, because it contributes to the build-up of CO_2 in the atmosphere. Furthermore, the non-linear responses obtained, along with their geographical and temporal variation, highlight the importance of considering the ecosystem responses to various pressures simultaneously.

4. What is the potential role of the terrestrial biosphere in climate change policy?

*In order t*o limit future climate change and its impacts, the U*nited Nations Framework Convention on Climate Change (UNFCCC) aims* to "stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system". In addition to emission reductions from energy use, the Kyoto Protocol under the UNFCCC provides explicit opportunities for developed countries to achieve some of their reduction commitments by planting new forests (so-called C plantations) or by managing existing forests or agricultural land in a different manner. This are the so-called Land Use and Land-Use Change and Forestry activities (LULUCF).

I presented and applied a new methodology here to assess different global and regional sequestration potentials in C plantations, along with their effectiveness in stabilizing the CO_2 concentration in the atmosphere. The methodology – as implemented in the IMAGE 2 model – considers various limitations and concerns, as formulated in the Kyoto Protocol. This has not yet been achieved in other climate change mitigation studies.

Application of the methodology for two different baseline scenarios up to 2100 indicates that uncertainties in future land-use change may lead to a near 100% difference in estimates of carbon sequestration potentials. Moreover, social barriers that prevent carbon plantations in natural vegetation areas may decrease the carbon sequestration potential by 75-80%. Nevertheless, taking the most conservative set of assumptions into consideration with respect to the land availability for food/feed production and the biodiversity concerns, carbon plantations could compensate for 5-7% of the energy and industry emissions up to 2100. The sequestration potential up to 2020 (incl. the first commitment period) is limited, given the short-term increased need for agricultural land in many regions and the long period needed to compensate for emissions during the establishment of new plantations. The largest potential develops beyond 2050 when more land becomes available and when established plantations start to sequester considerable amounts of carbon per unit area. Geographically, the C sequestration potential is highest in the tropics, although most of the agricultural expansion is also expected in these regions. The potential in high latitudes is limited and can even be unfavorable because of biogeophysical feedbacks. Plantations in these areas should only be established if the objective to sequester carbon is combined with other objectives like land protection or water management.

Based on a literature assessment, in general, and the IMAGE-2 application, in particular, I conclude that carbon plantations can play a large role in mitigating the build-up of atmospheric CO_2. The size of the role depends on the rules and accounting methods used and the timeframe considered. Furthermore, a number of ancillary benefits for local communities and the environment exist. Carbon plantations are, however, only effective in the long term. Furthermore, carbon plantations are not the ultimate solution to a stabilization of the CO_2 concentration. They must be part of a broader package of options with energy-emission reduction measures.

Although the only slight attention in climate change policy, the general behavior of the terrestrial biosphere is also important in defining policy measures required to stabilize greenhouse gas concentrations; The current terrestrial sink slows down the increase in atmospheric $CO_{2.}$ A robust finding among experiments presented here, but also in other studies, is a decrease in this sink after 2050. Such a decrease would imply more stringent emission reductions to achieve the UNFCCC objective of stabilizing GHG concentrations in the atmosphere.

5. What is the applicability of intermediate-complexity models to simulate the past, current, and future C cycle, especially in the context of climate change policy development?

The backbone of this thesis is the terrestrial C-cycle model of IMAGE 2. Applications of the model have led to the results and conclusions cited above. Compared to many other studies, the C cycle is assessed in an integrated manner, simultaneously considering socio-economic drivers and natural processes, along with their interactions and feedbacks.

The terrestrial C cycle is determined by numerous interacting processes that change over time and space. The processes include land use, and biogeochemical, biophysical, and ecological processes. Due to the complexity of the C cycle in the "real" world, the structure and processes are simplified in any terrestrial C cycle model. The problem in modeling the C cycle is to find an "optimal" extent of simplification. This is especially dependent on the objective of a model. IMAGE 2, as an example of Integrated Assessment (IA) models, is developed for primarily policy support. Particularly for these IA models, it is a major challenge to bridge the gap between policy needs (e.g. multiple-scenario analysis) and scientific rigor. This can only be achieved by a more reduced form of representation of various processes. Furthermore, detailed 'information' must be translated into general policy-relevant indicators and conclusions. In this thesis I presented different concepts on how such information could be communicated.

The IMAGE-2 C-cycle model is a model of intermediate complexity. Its algorithms are derived from yield, gap, biogeographical and especially biogeochemical models. Compared to simpler C-cycle models, IMAGE 2 is more process-based (including numerous interactions and feedbacks) and geographically explicit. The latter is important because the processes that determine the C cycle vary in space. Compared to more complex C-cycle models like DGVMs, various simplifications have been implemented in IMAGE 2 with respect to processes and scales. Ecosystem growth, for example, is implemented by using an average NPP value (for each biome) that is adjusted for climatic and local conditions. Furthermore, processes that determine the short-term C cycle (e.g. disturbances) and biogeophysical characteristics (e.g. surface roughness) are not included in the model.

The C pools and fluxes presented in simulations with IMAGE 2 are consistent with observations and findings of more detailed models on time scales ranging from decades to centuries. Applying the IMAGE-2 model for the past three centuries, for example, has yielded a well-reproduced atmospheric CO_2 concentration profile. The present-day NPP is about 60 Pg C yr^{1}, fitting well into the range of 58-62 Pg C yr^{1} cited in the literature. In projecting the future C cycle, IMAGE 2 estimates an NEP increase in the 1st half of the 21st century, followed by a decline. Qualitatively, this trend is in line with many other models.

Quantitatively, some of the projected C fluxes are at the high end of existing ranges, probably due to a CO_2 fertilization effect that is too strong and an underestimation of changes in soil decomposition. Some of these assumptions should be adjusted in new IMAGE 2 versions to reflect the most recent insights, as was undertaken for IMAGE, version 2.4 (MNP, chapter 5).

On the basis of the comparison with the observations and with other model structures and results, I conclude that the IMAGE-2 C-cycle model has certain limitations with respect to simulating fine-scale (e.g. small-country or even grid) or very dynamic (e.g. seasonal or inter-annual) information. Furthermore, because of intermediate complexity and the limited characterization of biophysical processes, the IMAGE-2 C cycle model seems less suited to be coupled to complex climate models, something planned on the longer term. The IMAGE 2 C-cycle model is, however, an appropriate model for simulating the global and continental dynamics of the terrestrial C cycle on decadal to century time scales. Furthermore, due to its simplicity, simulating multiple scenarios is possible and assumptions can easily be changed or dropped. Using alternative assumptions enables a systematic evaluation of the robustness of the findings. Finally, due to the integration in a larger modeling framework, the effect of other processes relevant to the terrestrial C cycle (e.g. land use and socioeconomic developments) can be compared with uncertainties in the terrestrial C cycle. The integration also provides the possibility of quantifying policy-relevant indicators like atmospheric CO_2 concentration and global average temperature.

7.3. Overall conclusions

- The dynamics in the terrestrial biosphere play a critical role in determining the C cycle, the atmospheric CO_2 concentrations and thus the global climate on time scales ranging from months/seasons to centuries.
- Both natural processes and land use (changes) determine the C dynamics in the terrestrial biosphere. The importance of the underlying processes varies over time and geographical space. This creates a need for an integrated and geographically explicit approach for accurately determining the behavior of the future C cycle as a consequence of changes in energy use, land use, and environmental conditions.
- The IMAGE-2 C-cycle model is an appropriate model for simulating the global and continental dynamics of the terrestrial C cycle on time scales of decades to centuries.
- The terrestrial biosphere can play an important role in “stabilizing the greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous

anthropogenic interference with the climate system". This important role has received insufficient attention in mitigation studies. However, given the importance of the energy sector, solely focusing in climate policies on slowing down deforestation or enhancing afforestation will not be sufficient for mitigating climate change.

- Different uncertainties in the biosphere –the future terrestrial sink, the role of land use, and the sequestration potential of C plantations – have large consequences for the C cycle. This can have considerable consequences for policy measures needed to achieve greenhouse gas stabilization. Reducing some of these uncertainties by developing robust parameterizations for processes like CO_2 fertilization should be a key issue in climate change research.

References

Achard F, Eva HD, Stibig HJ, Mayaux P, Gallego J, Richards T, Malingreau J-P (2002) Determination of Deforestation Rates of the World's Humid Tropical Forests. *Science* **297**, 999-1002.

Aerts R (2006) The freezer defrosting: global warming and litter decomposition rates in cold biomes. *Journal of Ecology,* **94**, 713-724.

Alcamo J, Kreileman GJJ, Krol M, Leemans R, Bollen J, Van Minnen JG, Schaefer F, Toet S, De Vries B (1998) Global modelling of environmental change: An overview of IMAGE 2.1. In: *Global change scenarios of the 21st century. Results from the IMAGE 2.1 model* (eds. Alcamo J, Leemans R & Kreileman GJJ), Pergamon Press/Elsevier Science, London. pp. 3-94.

Alexandrov GA, Oikawa T, Yamagata Y (2003) Climate dependence of the CO2 fertilization effect on terrestrial net primary production. *Tellus B,* **55**, 669-675.

An Y, Wan S, Zhou X, Subedar AA, Wallace LL, Luo Y (2005) Plant nitrogen concentration, use efficiency, and contents in a tall grass prairie ecosystem under experimental warming. *Global Change Biology,* **11**, 1733-1744.

Angert A, Biraud S, Bonfils C, Henning CC, Buermann W (2005) Drier summers cancel out the CO2 uptake enhancement induced by warmer springs. *Proceedings of the National Academy of Science,* **102**, 10823-10827.

Apps M (2003) Disturbances and earth system dynamics. *Global Change Newsletter,* **55**, 4-7.

Apps MJ, Kurz WA, Beukema SJ, Bhatti JS (1999) Carbon budget of the Canadian forest product sector. *Environmental Science and Policy,* **2**, 25-42.

Araujo MB, Cabeza M, Thuiller W, Hannah L, Williams PH (2004) Would climate change drive species out of reserves? An assessment of existing reserve-selection methods. *Global Change Biology,* **10**, 1618pp.

Atjay GL, Ketner P, Duvigneaud P (1979) *Terrestrial primary production and phytomass.* Bolin B, Degens ET, Kempe S & Ketner P (eds) Scope Report nr.13 edn. Wiley & Sons, New York, pp 129-187.

Bailey RG (1996) *Ecosystem Geography*. Springer Scientific Publisher.204pp.

Bakema AH, De Boer KF, Braat LC, Kok RM, Meijers R, Van Minnen JG (1994) EXPECT: A concise simulation system for environmental policy analysis. *Ecological Modelling,* **75/76**, 553-561.

Baker T, Phillips OL, Malhi Y, Almeida S, Arroyo L, Di Fiore A, Erwin T, Higuchi N, Killeen TJ, Laurance SG, Laurance WF, Lewis SL, Monteagudo A, Neill DA, Vargas PN, Pitman NCA, Silva NM, Martínez RV (2004) Increasing biomass in Amazonian forest plots. *Philosophical Transactions of the Royal Society, Series B,* **359**, 353-365.

Bakkenes M, Eickhout B, Alkemade JRM (2006) Impacts of different climate stabilisation scenarios on plant species in Europe. *Global Environmental Change,* **16**, 19-28.

Baldocchi D, Valentini R, Running S, Oechel W, Dahlman R (2000) Strategies for measuring and modelling carbon dioxide and water vapour fluxes over terrestrial ecosystems. *Global Change Biology,* **2**, 159-168.

Baldocchi DD (1993) Scaling water vapor and carbon dioxide exchange from leaves to a canopy: rules and tools. In: *Scaling Physiological Processes: Leaf to Globe* (eds. Ehleringer JR & Field CB). Academic Press, San Diego. pp. 77-114.

Baldocchi DD, Harley PC (1995) Scaling carbon dioxide and vapour exchange from leaf to canopy in a deciduous forest. II: Model testing and application. *Plant, Cell and Environment,* **18**, 1157-1173.

Balzter H (2000) Markov chain models for vegetation dynamics. *Ecological Modelling,* **126**, 139-154.

Bartholome E, Belward AS, Achard F, Bartalev S, Carmonamoreno C, Eva H, Fritz S, Gregoire J-M, Mayaux P, Stibig H-J (2002) *Global land cover mapping for the year 2000.* Joint Research Centre, ISPRA, Italy, 63 pp.

Batjes N (1998) Mitigation of atmospheric CO2 concentrations by increased carbon sequestration in the soil. *Biology and fertility of soils,* **27**, 230-235.

Bazzaz FA (1990) The response of natural ecosystems to the rising global CO_2 levels. *Annual Review of Ecology and Systematics,* **21**, 167-196.

Bazzaz FA (1998) Tropical forests in future climate: Changes in biological diversity and impact on the global carbon cycle. *Climatic Change,* **39**, 319-336.

Bazzaz FA, Fajer ED (1992) Plant life in a CO_2-rich world. *Scientific American,* **1992**, 18-21.

Bazzaz FA, Garbutt K, Reekie EG, Williams WE (1989) Using growth analysis to interpret competition between a C3 and a C4 annual under ambient and elevated CO2. *Ocologia,* **79**, 223-235

Beerling DJ, Mayle FE (2006) Contrasting effects of climate and CO2 on Amazonian ecosystems since the last glacial maximum. *Global Change Biology,* **12**, 1977-1984.

Benítez PC, McCallum I, Obersteiner M, Yamagata Y (2006) Global potential for carbon sequestration: Geographical distribution, country risk and policy implications. *Ecological Economics,* **60(3)**, 572-583; doi:10.1016/j.ecolecon.2005.12.015

Berg B, Tamm CO (1994) Decomposition and nutrient dynamics of litter in long-term optimum nutrient experiments II: Nutrient concentration in decomposing Picea abies needle litter. *Scandinavian Journal of Forest Research,* **9**, 99-105.

Berthelot M, Friedlingstein P, Ciais P, Dufresne J-L, Monfray P (2005) How uncertainties in future climate change predictions translate into future terrestrial carbon fluxes. *Global Change Biology,* **11**, 959-970.

Betts RA (2000) Offset of the potential carbon sink from boreal forestation by decreases in surface albedo. *Nature,* **408**, 187-190.

Birdsey RA, Jenkins JC, Johnston M, Huber-Sannwald E (2006) Chapter 11. North America Forests. In: *The State of the Carbon Cycle Report (SOCCR)* (ed. Zimmerman G), ORNL, http://cdiac.ornl.gov/SOCCR/index.html, 28 pp

Bolin B, Ciais P, Cramer WP, Jarvis PG, Kheshgi HS, Nobre CA, Semenov SM, Steffen WL, Linder S, Joos F (2000) Global perspective. In: *Land use, land-use change and forestry* (eds. Watson RT, Noble IR, Bolin B, Ravindranath NH, Verardo DJ & Dokken DJ),. Cambridge University Press, Cambridge. pp. 23-51

Bonan GB (2001) Observational evidence for reduction of daily maximum temperature by croplands in midwest United States. *Journal of Climate,* **14**, 2430-2442.

Botkin DB, J.F. Janak & J.R. Wallis. (1972) Some ecological consequences of a computer model of forest growth. *Journal of Ecology.,* **60 (3).** 849-873.

Bouwman AF, Van Ierland EC, Fresco LO, Kok F, C. Kroeze C, Schoorl J, Schotten K, Verburg P (1996) Scales and land Use/Land Cover Change. Proceedings Workshop *Scaling biogeochemical processes in space and time*, Wageningen,.6pp

Bowes G (1993) Facing the inevitable: plants and increasing atmospheric CO_2. *Annual Review of Plant Physiology and Plant Molecular Biology,* **44**, 309-332.

Box EO (1988) Estimating the seasonal carbon source-sink geography of a natural, steady-state terrestrial biosphere. *Journal of Applied Meteorology,* **27**, 1109-1124.

Bratley P, Fox BL, Schrage LE (1987) *A Guide to Simulation*. Springer, new York; 424pp.

Brinkman S, Strengers B, Van Minnen JG, Nabuurs GJ, Trines E (2005) *IMAGE 2.2. Carbon Cycle analysis.* Netherlands Environmental Assessment Agency, Bilthoven, 34 pp.

Brovkin V, Claussen M, Driesschaert E, Fichefet T, Kicklighter D, Loutre MF, Matthews HD, Ramankutty N, Schaeffer M, Sokolov A (2006) Biogeophysical effects of historical land cover changes simulated by six Earth system models of intermediate complexity. *Climate Dynamics,* **26**, 587-600.

Brovkin V, Ganopolski A, Svirezhev Y (1997) A continous climate-vegetation classification for the use in climate-biosphere studies. *Ecological Modelling,* **101**, 251-261.

Brown C (2000) *The global outlook for future wood supply from forest plantations.* FAO, Rome, 141 pp.

Brown P (1998) *Climate, biodiversity and forests: Issues and opportunities emerging from the Kyoto Protocol.* World Resource Institute (WRI), Washington DC, USA, 42 pp

Bruinsma JE (2003) *Agriculture: Towards 2015/2030. An FAO Perspective*. Earthscan, London, 432 pp.

Bugmann H, Grote R, Lasch P, Lindner M, Suckow F (1997) A new forest gap model to study the effects of environmental change on forest structure and functioning. In: *Impact of climate change on tree physiology and forest ecosystems* (eds. Mohren GMJ, Kramer K & Sabaté S), Kluwer, pp. 255-261.

Bugmann H, Lindner M, Lasch P, Flechsig M, Ebert B, Cramer W (2000) Scaling issues in forest succession modelling. *Climatic Change,* **44**, 265-289.

Bugmann H, Martin P (1995) How physics and biology matter in forest gap models. *Climatic Change,* **29**, 251-257.

Bugmann HKM, Yan X, Sykes MT, Martin P, Lindner M, Desanker P, Cumming S (1996) A comparison of forest gap models: Model structure and behaviour. *Climatic Change,* **34**, 289-313.

Burke IC, Lauenroth WK, Parton WJ, Cole CV (1994) Interaction between land use and global change in the central grasslands of the US: A geographic and simulation approach. *Global Ecology and Biogeography Letters,*

Burke IC, Schimel DS, Yonker CM, Parton WJ, Joyce LA, Lauenroth WK (1991) Regional modeling of grassland biogeochemistry using GIS. Landscape Ecology 4, 45-54.

Busing RT (2007) *A Spatial Landscape Model of Forest Patch Dynamics and Climate Change.* US Geological Survey, Reston, Virginia, 50 pp.

Campbell BD, Stafford Smith DM, McKeon GM (1997) Elevated CO2 and water supply interactions in grasslands: a pastures and rangelands management perspective. *Global Change Biology,* **3**, 177-187.

Cannell MGR (1982) *World Forest Biomass and Primary Production Data*. Academic Press, New York, 391pp.

Cannell MGR (2003) Carbon sequestration and biomass energy offset: Theoretical, potential and achievable capacities globally, in Europe and the UK. *Biomass and Bioenergy,* **24**, 97-116.

Cao M, Woodward FI (1998) Dynamic responses of terrestrial ecosystem carbon cycling to global climate change. *Nature,* **393**, 249-252.

Cash DW, Adger WN, Berkes F, Garden P, Lebel L, Olsson P, Pritchard L, Young O (2006) Scale and Cross-Scale Dynamics: Governance and Information in a Multilevel World. Ecology and Society, 11, 8, http://www.ecologyandsociety.org/vol11/iss2/art8/.

CDIAC (2006) ttp://cdiac.ornl.gov

Chen W, Chen JM, Price DT, Cihlar J, Liu J (2000) Carbon offset potentials of four alternative forest management strategies in Canada: a simulation study. *Mitigation and Adaptation Strategies for Global Change,* **5**, 143-169.

Churkina G, Schimel D, Braswell BH, Xiao X (2005) Spatial analysis of growing season length control over net ecosystem exchange. *Global Change Biology,* **11**, 1777-1787.

Ciais P, Tans PP, Denning AS, Francey RJ, Trolier M, Meijer HAJ, White JWC, Berry JA, Randall DA, Collatz GJ, Sellers PJ, Monfray P, Heimann M (1997) A three-dimensional synthesis study of d18O in atmospheric CO2. 1. Surface fluxes. *Journal of Geophysical Research,* **102**, 5857-5872.

Claussen M (1994) Coupling global biome models with climate models. *Climate Research,***4**,203-221.

Claussen M (1996) Variability of global biome patterns as a function of initial and boundary conditions in a climate model. *Climate Dynamics,* **12**, 371-379.

Cox P (2001) *The terrestrial carbon cycle model TRIFFID.* Hadley Centre, Oxford, 4 pp.

Cox PM, Betts RA, Collins M, Harris PP, Huntingford C, Jones CD (2004) Amazon dieback under climate-carbon cycle projections for the 21st century. *Theoretical Appl. Climatology,***78**,137-156.

Cox PM, Betts RA, Jones CD, Spall SA, Totterdell IJ (2000) Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. **408**, 180-184.

CPB (1999) *WorldScan: the core version*. CPB Netherlands Bureau for Economic Policy Analysis, The Hague.137p.

Cramer W, Bondeau A, Schaphoff S, Lucht W, Smith B, Sitch S (2004) Tropical forests and the global carbon Cycle: Impacts of atmospheric carbon dioxide, climate change and rate of deforestation. *Philosophical Transactions of the Royal Society of London-Series B,* **359**, 331-343.

Cramer W, Bondeau A, Woodward I, Prentice IC, Betts R, Brovkin V, Cox P, Fisher V, Foley JA, Friend AD, Kucharik C, Lomas M, Sitch S, Smith B, White A, Young -M, C. (2001) Global response of terrestrial ecosystem structure and function to CO2 and climate change: results from six dynamic global vegetation models. *Global Change Biology,* **7**, 357-373.

Cramer W, Field CB (1999) Comparing global models of terrestrial net primary productivity (NPP): Introduction. *Global Change Biology,* **5**, iii-iv.

Cramer W, Kicklighter DW, Bondeau A, Moore III B, Churkina G, Nemry B, Schloss AL, workshop PoPNmi (1999) Comparing global models of terrestrial net primary productivity (NPP): Overview and key results. *Global Change Biology,* **5**, 1-15.

Cramer W, Leemans R, Schulze E-D, Bondeau A, Scholes RJ (1999) Data needs and limitations for broad-scale ecosystem modelling. In: *The terrestrial biosphere and global change. Implications for natural and managed ecosystems* (eds. Walker B, Steffen W, Canadell J & Ingram J),. Cambridge University Press, pp. 88-105

Cramer W, Solomon AM (1993) Climatic classification and future global redistribution of agricultural land. *Climate Research,* **3**, 97-110.

Davidson EA, Janssens JA (2006) Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. *Nature,* **440**, 165-173.

Davis MB (1981) Quaternary history and the stability of forest communities. In: *Forest Succession: Concepts and Application* (eds. West DC, Shugart HH & Botkin DB), Springer-Verlag, New York. pp. 132-154.

Davis MB, Sugita S (1997) Reinterpreting the fossil pollen record of Holocene tree migration. In: *Past and future rapid environmental changes. The spatial and evolutionary responses of terrestrial biota* (eds. Huntley B, Cramer W, Morgan AV, Prentice HC & Allen JRM), Springer pp. 181-193.

Davis MB, Zabinski C (1992) Changes in geographical range resulting from greenhouse warming: effects on biodiversity in forests. In: *Global Warming and Biological Diversity* (eds. Peters RL & Lovejoy TE), Yale University Press, New Haven. pp. 297-308.

De Jong HJ (2000) *Forestry for mitigating the greenhouse effect: An ecological and economic assessment of the potential of land use to mitigate CO2 emissions in the highlands of Chiapas, Mexico.* PhD, Wageningen University, Wageningen, The Netherlands, 220 pp.

De Vries WIM, Reinds GJ, Gundersen PER, Sterba H (2006) The impact of nitrogen deposition on carbon sequestration in European forests and forest soils. *Global Change Biology,* **12**, 1151-1173.

Deckmyn G, Muys B, Garcia Quijano J, Ceulemans R (2004) Carbon sequestration following afforestation of agricultural soils: comparing oak/beech forest to short-rotation poplar coppice combining a process and a carbon accounting model. *Global Change Biology,* **10**, 1482-1491.

DeFries RS, Houghton RA, Hansen MC, Field CB, Skole D, Townshend J (2002) Carbon emissions from tropical deforestation and regrowth based on satellite observations for the 1980s and 1990s. *PNAS,* **99**, 14256-14261.

Del Lungo A (2003) *Planted forest database: Analysis of annual planting trends and silvicultural parameters for commonly planted species.* FAO, Rome, 60 pp.

Denman KL, Brasseur G, Chidthaisong A, Ciais P, Cox P, Dickinson RE, Hauglustaine D, Heinze C, Holland E, Jacob D, Lohmann U, Ramachandran S, Dias PLdS, Wofsy SC, Zhang X (2007) Couplings Between Changes in the Climate System and Biogeochemistry. In: *Climate Change 2007: The Physical Science Basis* (eds. Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt K, Tignor MMB & Miller HL),. Working Group 1 Contribution to the Fourth Assessment Report of the Intergovernmental Panell on Climate Change (IPCC) pp. 499 - 588

DePury DGG, Ceulemans R (1997) Scaling-up carbon fluxes from leaves to stands in a patchy coniferous/deciduous forest. In: *Simulation of direct effects of* CO_2 *and temperature increase on forest growth: The LTEEF project* (eds. Mohren GMJ, Kramer K & Sabaté S), Kluwer Academic Press, Dordrecht, the Netherlands. pp. 263-272.

Dewar RC, Cannell MGR (1992) Carbon sequestration in the trees, products and soils of forest plantations: an analysis using UK examples. *Tree Physiology,* **11**, 49-71.

Diemont WH (1994) Effects of removal of organic matter on the productivity of heathlands. *Journal of Vegetation Science,* **5**, 409-414.

Dixon RK, Brown S, Houghton RA, Solomon AM, Trexler MC, Wisniewski J (1994) Carbon pools and flux of global forest ecosystems. *Science,* **263**, 185-190.

Dolman AJ, Hutjes RWA, Nabuurs GJ, Schelhaas MJ, ter Maat HW, Kabat P, Mors E, Huygen J, Haarsma R, Ronda RJ, Schaeffer M, Opsteegh JD, Leemans R, Bouwman AF, Busch G, Eickhout B, Kreileman E, Strengers B, de Vries B, Willemsen F, Dorland C, Tol RSJ, Verhagen J, Vleeshouwers L, Corre WJ, Jongschap REE, Kruseman G, van Ierland E, Holtslag AAM (2001) *Land use, climate and biogeochemical cycles: feedbacks and options for emission reduction.* Dutch National Research Programme on Global Air Pollution and Climate Change, Bilthoven, The Netherlands, 252 pp.

Dumont E (2007) *Identifying the appropriate scales in model nitrogen flows from land to water.* PhD, Wageningen University, Wageningen, the Netherlands, 141 pp

Dyer JM (1995) Assessment of climatic warming using a model of forest species migration. *Ecological Modelling,* **79**, 199-219.

EEA (2004) *Greenhouse gas emission projections and costs 1990-2030.* European Environmental Agency, Copenhagen, Denmark, 82 pp.

EEA (2004) *Impacts of Europe's changing climate: An indicator-based assessment.* European Environmental Agency, Copenhagen, 99 pp.

Eickhout B, den Elzen MGJ, Kreileman E (2004) *The atmosphere-ocean system in IMAGE 2.2. A global model approach for atmospheric concentrations, and climate and sea level projections.* National Institute of Public Health and the Environment, Bilthoven, 63 pp.

Eickhout B, Van Meijl H, Tabeau A (2006) Modelling agricultural trade and food production under different trade policies. In: *Integrated modelling of global environmental change. An overview of IMAGE 2.4* (ed. MNP (Bouwman AF, Kram, T., and Klein Goldewijk, K.), Netherlands Environmental Assessment Agency, Bilthoven. pp. 61-76.

Emanuel WR, Killough GG, Post WM, Shugart HH (1984) Modeling terrestrial ecosystems in the global carbon cycle with shifts in carbon storage capacity by land-use change. *Ecology,* **65**, 970-983.

Emanuel WR, Shugart HH, Stevenson MP (1985) Climatic change and the broad-scale distribution of terrestrial ecosystems complexes. *Climatic Change,* **7**, 29-43.

Faaij A, Agterberg A (2000) *Long-term perspectives for production of fuels from biomass; An integrated assessment and R&D priorities.* Dept. of Science, Technology and Society, Utrecht University, The Netherlands, Utrecht, .

Fan S, Gloor M, Mahlman J, Pacala S, Sarmiento J, Takahashi T, Tans P (1998) A large terrestrial carbon sink in North-America implied by atmospheric and oceanic Carbon Dioxide data and models. *Science,* **282**, 441-446.

Fang JY, Wang GG, Liu GH, Xu SL (1998) Forest biomass of China: An estimate based on the biomass-volume relationship. *Ecological Applications,* **8**, 1084-1091.

FAO (2001) *Global forest resources assessment 2000: Main report.* Food and Agriculture Organisation of the United Nations, Rome, 479 pp.

FAO (2004) *Assessing carbon stocks and modelling win-win scenarios of carbon sequestration through land-use changes.* FAO, Rome, 68 pp.

FAO (2006) *FAOSTAT database collections.* Food and Agriculture Organisation of the United Nations, Rome, pp.

Fearnside PM (2000) Accounting for time in mitigation global warming through land-use change and forestry. *Mitigation and Adaptation Strategies for Global Change,* **5**, 239–270

Fearnside PM (2000) Global warming and tropical land-use change: Greenhouse gas emissions from biomass burning, decomposition and soils in forest conversion, shifting cultivation and secondary vegetation. *Climatic Change,* **46**, 115-158.

Fearnside PM (2001) The potential of Brazil forest sector for mitigating global warming under the Kyoto Protocol. *Mitigation and Adaptation Strategies for Global Change,* **6**, 355-372.

Field CB (1991) Ecological Scaling of Carbon gain to stress and resource availability. In: *Response of Plants to Multiple Stress*,. Academic Press, London. pp. 35-65

Fischlin A, Midgley GF, Price J, Leemans R, Gopal B, Turley C, Rounsevell M, Dube P, Tarazona J, Velichko A (2007) Ecosystems, their Properties, Goods, and Services. In: *Climate Change 2007: Impacts, Vulnerability and Adaptation* (eds. Parry M, Canziani O, Palutikof J, Hanson C, Linden Pvd & Pritchard N). Chapter 4 to Working Group 2 Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) pp 211-277

Foley J, Levis S, Prentice I, Pollard D, Thompson S (1998) Coupling dynamic models of climate and vegetation. *Global Change Biology,* **4**, 561-579.

Foley JA, Ramankutty N (2004) A primer on the terrestrial carbon cycle: What do we don't know but should. In: *The global carbon cycle: Integrating humans, climate and the natural world* (eds. Field CB & Raupach MR),. Island Press, Washington. pp. 279-294

Friedlingstein P, Cox P, Betts R, Bopp L, Bloh WV, Brovkin V, Cadule P, Doney S, Eby M, Fung I, Bala G, John J, Jones C, Joos F, Kato T, Kawamiya M, Knorr W, Lindsay K, Matthews HD, Raddatz T, Rayner P, Reick C, Roeckner E, Schnitzler K-G, Schnur R, Strassmann K, Weaver AJ, Yoshikawa C, Zeng N (2006) Climate–Carbon Cycle Feedback Analysis: Results from the C4MIPModel Intercomparison. *Journal of Climate.,* **19**, 3337-3353.

Friedlingstein P, Dufresne J-L, Cox PM, Rayner P (2003) How positive is the feedback between climate change and the carbon cycle? *Tellus B,* **55B**, 692-700.

Friedlingstein P, Fung I, Holland E, John J, Brasseur G, Erickson D, Schimel D (1995) On the contribution of CO_2 fertilization to the missing biospheric sink. *Global Biogeochemical Cycles,* **9**, 541-556.

Friedlingstein P, Muller JF, Brasseur GP (1994) Sensitivity of the terrestrial biosphere to climate changes: Impact on the carbon cycle. *Environmental Pollution,* **83**, 143-147.

Friend AD, Arneth A, Kiang NY, Lomas M, Ogee J, Rodenbeck C, Running SW, Santaren J-D, Sitch S, Viovy N, Ian Woodward F, Zaehle S (2007) FLUXNET and modelling the global carbon cycle. *Global Change Biology,* **13**, 610-633.

Friend AD, Stevens AK, Knox RG, Cannell MGR (1997) A process-based terrestrial; biosphere model of ecosystem dynamics (Hybrid v3.0). *Ecological Modelling,* **95**, 249-287.

Fulton MR (1993) Rapid simulations of vegetation stand dynamics with mixed life-forms. In: *Vegetation Dynamics and Global Change* (eds. Solomon AM & Shugart HH), Chapman and Hall, New York. pp. 251-271.

Füssel HM, Toth FL, Van Minnen JG, Kaspar F (2003) Climate impact response functions as impact tools in the tolerable windows approach. *Climatic Change,* **56**, 91-117.

Gallimore R, Jacob R, Kutzbach J (2005) Coupled atmosphere-ocean-vegetation simulations for modern and mid-Holocene climates: role of extratropical vegetation cover feedbacks. *Climate Dynamics,* **25**, 755-776.

Gervoisa S, Noblet-Ducoudréa Nd, Viovya N, Ciaisa P, Brissonb N, Seguinb B, Perrierc A (2004) Including Croplands in a Global Biosphere Model: Methodology and Evaluation at Specific Sites. *Earth Interactions,* **8**, 1-25.

Giardina CP, Ryan MG (2000) Evidence that decomposition rates of organic carbon in mineral soil do no vary with temperature. *Nature,* **404**, 858-860.

Gibson C, Ostrom E, Ahn T-K (2000) The concept of scale and the human dimensions of global change: a survey. *Ecological Economics,* **32**, 217-239.

Gielen DJ, De Feber MAPC, Bos AJM, Gerlagh T (2001) Biomass for energy or materials? A Western European system engineering perspective. *Energy Policy,* **29**, 291-302.

Gitay H, Brown S, Easterling WE, Jallow B, Antle J, Apps M, Beamisch R, Chapin T, Cramer W, Frangi J, laine J, Erda L, Magnuson J, Noble I, Price J, Prowse T, Root TL, Schulze E-D, Sirotenko O, Sohngen B, Soussane J (2001) Ecosystems and their goods and services. In: *Climate change 2001: Impacts, Adaptation, and Vulnerability; Contribution of working group II to the 3rd assessment report of the IPCC,* (eds. McCarthy JJ, Canziani OF, Leary NA, Dokken DJ & White KS). Cambridge University Press, London & New York pp. 235-342

Gorham E (1991) Northern peatlands: role in the carbon cycle and probable responses to climatic warming. *Ecological Applications,* **1**, 181-195.

Goudriaan J (1996) Opschalen bij plant en vegetatie. Proceedings Workshop *Scaling biogeochemical processes in space and time*, Wageningen,.4pp .

Goudriaan J, De Ruiter HE (1983) Plant growth in response to CO_2 enrichment, at two levels of nitrogen and phosphorus supply. 1. Dry matter, leaf area and development. *Netherlands Journal of Agricultural Science,* **31**, 157-169.

Goudriaan J, Ketner P (1984) A simulation study for the global carbon cycle, including man's impact on the biosphere. *Climatic Change,* **6**, 167-192.

Goudriaan J, Shugart HH, Bugmann H, Cramer W, Bondeau A, Gardner RH, Hunt LA, Lauenroth WK, Landsberg JJ, Sinder S, Noble IR, Parton WJ, Pitelka LF, Stafford Smith M, Sutherst RW, Valentin C, Woodward I (1999) Use of models in global change studies. In: *The terrestrial biosphere and global change. Implications for natural and managed ecosystems* (eds. Walker B, Steffen W, Canadell J & Ingram J),. Cambridge University Press pp. 106-145

Goudriaan J, Zadoks JC (1995) Global climate change: modelling the potential responses of agro-ecosystems with special reference to crop protection. *Environmental Pollution,* **87**, 215-224.

Grace J (2004) Understanding and managing the global carbon cycle. *Journal of Ecology,* **92**, 189-202.

Gracia C, Sabate S (2002) Aboveground biomass expansion factors and biomass equations of forests in Catalonia. *CREAF expert meeting on biomass expansion factors (BEF)*, Valencia, 5 pp

Grime JP (1993) Vegetation functional classification systems as approaches to predicting and quantifying global vegetation change. In: *Vegetation Dynamics and Global Change* (eds. Solomon AM & Shugart HH),. Chapman and Hall, New York. pp. 293-305

Gruber N, Friedlingstein P, Field CB, Valentini R, Heinmann M, Richey JE, Lankao PR, Schulze ED, Chen C-TA (2004) The vulnerability of the carbon cycle in teh 21st century: An assessment of carbon-climate-human interactions. In: *The global carbon cycle: Integrating humans, climate and the natural world* (eds. Field CB & Raupach MR),. Island Press, Washington. pp. 45-76

GTAP (2004) *The GTAP 6 Data package.* Purdue University, USA, https://www.gtap.agecon.purdue.edu/databases/v6/default.asp

Guisan A, Thuiller W (2005) Predicting species distribution: Offering more than simple habitat models. *Ecological Letters,* **8**, 993-1009.

Gurney KR, Law RM, Denning AS, Rayner PJ, Baker D, Bousquet P, Bruhwilerk L, Chen Y-H, Ciais P, Fan S, Fung IY, Gloor M, Heimann M, Higuchi K, John J, Maki T, Maksyutov S, Masariek K, Peylin P, Prather M, Pak BC, Randerson J, Sarmiento J, Taguchi S, Takahashi T, Yuen C-W (2002) Towards robust regional estimates of CO2 sources and sinks using atmospheric transport models. *Nature,* **415**, 626-630.

Hall DO, Mynick HE, Williams RH (1991) Cooling the greenhouse with bioenergy. *Nature,* **353**, 11-12.

Hamilton C, Vellen L (1999) Land-use changes in Australia and the Kyoto protocol. *Environmental Science & Policy,* **2**, 135-144.

Hannah L, Carr JL, Landerani A (1995) Human disturbance and natural habitat: a biome level analysis of a global data set. *Biodiversity and Conservation,* **4**, 128-155.

Harvey LDD (1989) Transient climatic responses to an increase of greenhouse gases. *Climatic Change,* **15**, 15-30.

Haxeltine A, Prentice C (1996) BIOME3: An equilibrium terrestrial biosphere model based on ecophysiological constraints, resource availability, and competition among plant functional types. *Global Biogeochemical Cycles,* **10**, 693-709.

Heath J, Ayres E, Possell M, Bardgett RD, Black HIJ, Grant H, Ineson P, Kerstiens G (2005) Rising Atmospheric CO2 Reduces Sequestration of Root-Derived Soil Carbon. *Science,* **309**, 1711-1713.

Hegerl GC, Zwiers FW, Braconnot P, Gillett NP, Luo Y, Marengo J, Nicholls N, Penner JE, Stott PA (2007) Understanding and Attributing Climate Change. In: *Climate Change 2007: The Physical Science Basis* (eds. Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt K, Tignor MMB & Miller HL), Working Group 1 Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA pp. 663-746.

Heinmann M, Esser G, Haxeltine A, Kaduk J, Kicklighter DW, Knorr W, Kohlmaier GH, McGuire AD, Melillo J, Moore III B, Otto RD, Prentice IC, Sauf W, Schloss A, Sitch S, Wittenberg U, Würth G (1998) Evaluation of terrestrial carbon cycle models through simulations of the seasonal cycle of atmospheric CO2: First results of a model intercomparison study. *Global Biogeochemical Cycles,* **12**, 124.

Hekkert MP (2000) *Improving material management to reduce greenhouse gas emissions*. PhD, Utrecht University, Utrecht, 217 pp .

Henderson-Sellers A, McGuffie K (1995) Global climate models and ‘dynamic’ vegetation changes. *Global Change Biology,* **1**, 61-75.

Hilderink HBM (2006) People in the pixel: Grid-based population dynamics using PHOENIX. In: *Integrated modelling of global environmental change. An overview of IMAGE 2.4* (ed. MNP (Bouwman AF, Kram, T., and Klein Goldewijk, K.), Netherlands Environmental Assessment Agency, Bilthoven. p 25-38

Hinssen PJW (1994) HOPSY, a model to support strategic decision making in forest resource management. *Forest Ecology and Management,* **69**, 321-330.

Hitz S, Smith JB (2004) Estimating global impacts from climate change. *Global Environmental Change,* **14**, 201-218.

Hoch G, Richter A, Körner C (2003) Non-structural carbon compounds in temperate forest trees. *Plant, Cell and Environment,* **26**, 1067-1081.

Hoffman WA, Schroeder W, Jackson RB (2002) Positive feedbacks of fire, climate, and vegetation and the conversion of tropical savanna. *Geophysical Reserach Letters,* **29(22)** 2052, doi:10.1029/2002GL015424.

Holdridge LR (1967) *Life Zone Ecology*. Tropical Science Center, San José, Costa Rica, .206pp

Hoogwijk M, Faaij A, Eickhout B, De Vries B, Turkenburg W (2005) Potential of biomass energy out to 2100 for four IPCC SRES land-use scenarios. *Biomass & Bioenergy,* **29**, 225-257.

Houghton RA (1991) Tropical deforestation and atmospheric carbon dioxide. *Climate Change.,* **19**, 99-118.

Houghton RA (2003) Revised estimates of the annual flux of carbon to the atmosphere from changes in land use and land management 1950-2000. *Tellus B,* **55**, 378-390.

Houghton RA, Hackler JL, Lawrence KT (1999) The US carbon budget: Contributions from land-use change. *Science,* **285**, 574-578.

Houghton RA, Hobbie JE, Meilillo JM (1983) Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: A net release of CO2 to the atmosphere. *Ecological Monograph.,* **53(3)**, 235-262.

Hougton RA (2002) Magnitude, distribution and causes of terrestrial carbon sinks and some implications for policy. *Climate Policy,* **69**, 1-18.

House JI, Prentice IC, Ramankutty N, Houghton RA, Heimann M (2003) Reconciling apparent inconsistencies in estimates of terrestrial CO2 sources and sinks. *Tellus B,* **55B**, 345-363.

Hungate BA, Dukes JS, Shaw MR, Luo Y, Field CB (2003) Nitrogen and Climate Change. *Science,***5650**, 1512-1513.

Hunt HW, Trlica MJ, Redente EF, Moore JC, Detling JK, Kittel TGF, Walter DE, Fowler MC, Klein DA, Elliott ET (1991) Simulation model for the effects of climate change on temperate grasland ecosystems. **53**, 205-240.

Huntley B, Cramer WP, Morgan AV, Prentice HC, Allen JRM (1997) *Past and future rapid environmental changes: the spatial and evolutionary responses of terrestrial biota*(eds). Springer, Berlin, 523 pp.

Huntley B, Webb T (1988) *Vegetation History*. Lieth H (eds). Kluwer Academic Publishers, Dordrecht, 803 pp.

Huntley B, Webb T, III (1989) Migration: Species' response to climatic variations caused by changes in the earth's orbit. *Journal of Biogeography,* **16**, 5-19.

Hurtt GC, Frolking S, Fearon MG, Moore B, Shevliakova E, Malyshev S, Pacala SW, Houghton RA (2006) The underpinnings of land-use history: three centuries of global gridded land-use transitions, wood-harvest activity, and resulting secondary lands. *Global Change Biology,* **12**, 1208-1229.

Huth A (2000) *Modellierung des Wachstums und der Nutzung von tropischen Regenwald*. Habilitation thesis, Report of the University of Kassel, Germany.

Ilic J, Boland D, McDonald M, Downes G, Blakemore P (2000) *Woody Density Phase 1 - State of Knowledge.* Australian Greenhouse Office, 234 pp.

IMAGE team (2001) *The IMAGE 2.2 implementation of the SRES scenarios: A comprehensive analysis of emissions, climate change and impacts in the 21st century.* National Institute of Public Health and the Environment, Bilthoven, CD rom publication 500110001

IPCC (2004) *Good Practice Guidance for Land Use, Land-Use Change and Forestry.* IPCC Special Report, 599 pp.

Jackson RB, Jobbagy EG, Avissar R, Roy SB, Barrett DJ, Cook CW, Farley KA, Maitre DCl, McCarl BA, Murray BC (2005) Trading Water for Carbon with Biological Carbon Sequestration. *Science,* **310**, 1944-1947.

Jamieson PD, Porter JR, Goudriaan J, Ritchie JT, van Keulen H, Stol W (1998) A comparison of the models AFRCWHEAT2, CERES-Wheat, Sirius, SUCROS2 and SWHEAT with measurements from wheat grown under drought. *Field Crop Research,* **55**, 23–44.

Janssens IA, Freibauer A, Ciais P, Smith P, Nabuurs G-J, Folberth G, Schlamadinger B, Hutjes RWA, Ceulemans R, Schulze E-D, Valentini R, Dolman AJ (2003) Europe's Terrestrial Biosphere Absorbs 7 to 12% of European Anthropogenic CO2 Emissions. *Science,* **300**, 1538-1542.

Jarvis PG (1995) Scaling processes and problems. *Plant, Cell and Environment,* **18**, 1079-1089.

Jenerette GD, Wu J (2000) On the Definitions of Scale. *Bulletin of the Ecological Society of America,* **81**, 104-105.

Joos F, Prentice IC, Sitch S, Meyer R, Hooss G, Plattner G-K, Gerber S, Hasselmann4 K (2001) Global warming feedbacks on terrestrial carbon uptake under the Intergovernmental Panel on Climate Change(IPCC) emission scenarios. *Global Biogeochemical Cycles,* **15**, 891-908.

Jump AS, Penuelas J (2005) Running to stand still: adaptation and the response of plants to rapid climate change. *Ecology Letters,* **8**, 1010-1020.

Kaduk J, Heinman M (1996) A prognostic phenology scheme for global terrestrial carbon-cycling models. *Climate Research,* **6**, 1-9.

Kaipainen T, Liski J, Pussinen A, Karjalainen T (2004) Managing carbon sinks by changing rotation length in European forests. *Enviornmental Science and Policy,* **7**, 205-219.

Karjalainen T (1996) Dynamics and potentials of carbon sequestration in managed stands and wood products in Finland under changing climatic conditions. *Forest Ecology and Management,* **2**, 165-175.

Karjalainen T, Pussinen A, Liski J, Nabuurs GJ, Eggers T, Lapvetelainen T, Kaipainen T (2003) Scenario analysis of the impacts of forest management and climate change on European forest sector carbon budget. *Forest Policy and Economics,* **5**, 141-155.

Kätterer T, Reichstein M, Andren O, Lomander A (1998) Temperature dependence of organic matter decomposition: A critical review using literature data analyzed with different models. *Biology and Fertility of Soils,* **27**, 258-262.

Kauppi P, Sedjo RJ, Apps M, Cerri C, Fujimori T, Janzen H, Krankina O, Makundi W, Marland G, Masera O, Nabuurs GJ, Razali W, Ravindranath NH (2001) *Technical and economic potential of options to enhance, maintain and manage biological carbon reservoirs and geo-engineering. WGIII contribution to* IPCC Third Assessment Report on Climate Change, Cambridge University Press, London, New York, pp 302-343 .

Keddy PA (2000) *Wetland ecology: Principles and conservation*. Cambridge University Press, Cambridge, UK., 614 p.

Keeling CD, Bacastow RB, Whorf TP (1982) Measurements of the concentration of Carbon Dioxide at Mauna Loa Observatory, Hawaii. In: *Carbon Dioxide Review* (ed. Clark WC),. Oxford University Press, New York. pp. 377-385

Keeling CD, Whorf TP (2001) Atmospheric CO2 records from sites in the SIO air sampling network. In: *Trends: A Compendium of Data on Global Change*. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tenn., U.S.A.

Keppler F, Hamilton JTG, Braß M, Röckmann T (2006) Methane emissions from terrestrial plants under aerobic conditions. *Nature,* **439**, 187-191.

Kimmins JP, mailly D, Seely B (1999) Modelling forest ecosystems net primary production: The hybrid simulation approach used in FORECAST. *Ecological Modelling,* **122**, 195-224.

King AW (1991) Translating models across scales in the landscape. In: *Quantative methods in landscape ecology* (eds. Turner MG & Gardner RH),. Springer Verlag pp. 479-517

Kirschbaum MF (2003) Can trees buy time? An assessment of the role of vegetation sinks as part of the global carbon cycle. *Climatic Change,* **58**, 47-71.

Kirschbaum MUF, Bruhn D, Etheridge DM, Evans JR, Farquhar GD, Gifford RM, Pau KI, Winters AJ (2006) A comment on the quantitative significance of aerobic methane release by plants. *Functional Plant Biology,* **33**, 521-530.

Klein Goldewijk K (2001) Estimating global land use change over the past 300 years: The Hyde database. *Global Biogeochemical Cycles,* **15**, 417-433.

Klein Goldewijk K (2005) Three centuries of global population growth: A spatial referenced population density database for 1700 – 2000. *Population and Environment,* **26**, 343-367.

Klein Goldewijk K, Leemans R (1995) System models of terrestrial carbon cycling. In: *Prospects for carbon sequestration in the bioshere.* (ed. Beran M), NATO ASI series pp 121-151

Klein Goldewijk K, Van Drecht G, Bouwman AF (2007) Mapping contemporary global cropland and rangeland on a 5’ resolution grid. *Journal of Land Use Science,* **2**, 167-190.

Klein Goldewijk K, Van Minnen JG, Kreileman GJJ, Vloedbeld M, Leemans R (1994) Simulation of the carbon flux between the terrestrial environment and the atmosphere. *Water, Air and Soil Pollution,* **76**, 199-230.

Klein Tank A (2004) *Changing Temperature and Precipitation Extremes in Europe’s Climate of the 20th Century*. PhD, Utrecht University, Utrecht, Pages , 124 pp.

Knorr W, Heinmann M (2001) Uncertainties in global terrestrial biosphere modeling, Part 1: A comprehensive sensitivity analysis with a new photosynthesis and energy balance scheme. *Global Biogeochemical Cycles,* **15**, 207-225.

Knorr W, Prentice IC, House JI, Holland EA (2005) Long-term sensitivity of soil carbon turnover to warming. *Nature,* **433**, 298-301.

Koch GW, Mooney HA (1996) Response of terrestrial ecosystem to elevated CO2: A synthesis and summary. In: *Carbon dioxide and terrestrial ecosystems* (eds. Koch GW & Mooney HA), Academic Press pp. 415-429.

Kohlmaier GH, Babeck FW, Otto RD, Häger C, Dönges S, Kindermann J, Würth G, Lang T, Jäkel U, Nadler A, Ramge P, Klaudius A, Habermehl S, Lüdeke MKB (1997) The Frankfurt Biosphere Model: A global process oriented model for the seasonal and longterm CO_2 exchange between terrestrial ecosystems and the atmosphere. II. global results for potential vegetation in an assumed equilibrium state. *Climate Research,* **8**, 61-87.

Körner C (1993) CO_2 fertilization: The great uncertainty in future vegetation development. In: *Vegetation Dynamics and Global Change* (eds. Solomon AM & Shugart HH),. Chapman and Hall, New York. pp. 53-70

Körner C (2003) Carbon limitations in trees. *Journal of Ecology,* **91**, 4-17.

Körner C (2003) Ecological impacts of atmospheric CO_2 enrichment on terrestrial ecosystems. *Philosophical Transaction,* **361**, 2023-2041.

Körner C (2003) Slow in, Rapid out--Carbon Flux Studies and Kyoto Targets. *Science,* **300**, 1242-1243.

Körner C, Asshoff R, Bignucolo O, Hattenschwiler S, Keel SG, Pelaez-Riedl S, Pepin S, Siegwolf RTW, Zotz G (2005) Carbon Flux and Growth in Mature Deciduous Forest Trees Exposed to Elevated CO2. *Science,* **309**, 1360-1362.

Körner C, Diemer M (1987) In situ photosynthetic responses to light, temperature and carbon dioxide in herbaceous plants from low and high altitude. **1**, 179-194.

Kramer K, Leinonen I, Bartelink HH, Berbigier P, Borghetti M, Bernhofer C, Cienciala E, Dolman AJ, Froer O, Gracia CA, Granier A, Grünwald T, Hari P, Jans W, Kellomäki S, Loustau D, Magnani F, Markkanen T, Matteucci G, Mohren GMJ, Moors E, Nissinen A, Peltola H, Sabaté S, Sanchez A, Sontag M, Valentini R, Vesala T (2002) Evaluation of six process-based forest growth models using eddy-covariance measurements of CO_2 and H_2O fluxes at six forest sites in Europe. *Global Change Biology,* **8**, 213-230.

Kramer K, Mohren GMJ (1996) Sensitivity of FORGRO to climate change scenarios: A case study on Betula pubescens, Fagus sylvatica and Quercus robur in the Netherlands. *Climatic Change,* **34**, 231-237.

Krankina ON, Harmon ME, Cohen WB, Doug R. Oetter, Zyrina O, Duane MV (2004) Carbon stores, sinks, and sources in forests of Northwestern Russia: Can we reconcile forest inventories with remote sensing results? *Climatic Change,* **67**, 257-272.

Krinner G, Viovy N, de Noblet-Ducoudre N, Ogee J, Polcher J, Friedlingstein P, Ciais P, Sitch S, Prentice IC (2005) A dynamic global vegetation model for studies of the coupled atmosphere-biosphere system. *Global Biogeochemical Cycles,* **19**, 1-33.

Kucharik CJ, Foley JA, Delire C, Fisher VA, Coe MT, Lenters J, Young-Molling C, Ramankutty N, Norman JM, Gower ST (2000) Testing the performance of a dynamic global ecosystem model: Water balance, carbon balance and vegetation structure. *Global Biogeochemical Cycles,* **14**, 795-825.

Kullman L (1996) New and firm evidence for Mid-Holocene appearance of Picea abies in the Scandes mountains, Sweden. *Journal of Ecology,* **83**, 439-447.

Kurz WA, Apps MJ, Beukema SJ, Lekstrum T (1995) 20th century carbon budget of canadian forests. *Tellus,* **47B**, 170-177.

Kurz WA, Apps MJ, Webb TM, McNamee PJ (1992) *The carbon budget of the Canadian forest sector: Phase I.* Northern Forestry Center, Information Report no. Report NOR-X-326, Canada, 93 pp

Lal R (2003) Global Potential of soil carbon sequestration to mitigate the greenhouse effect. *Critical Reviews in Plant Sciences,* **22**, 151-184.

Lal R, Bruce JP (1999) The potential of world cropland soils to sequester C and mitigate the greenhouse effect. *Environmental Science and Policy,* **2**, 177-185.

Lam N (2004) Fractals and scale in environmental assessment and monitoring. In: *Scale and Geographic Inquiry* (eds. Sheppard E & McMaster RB), pp. 23-40

Lambin EF, Geist HJ, Lepers E (2003) Dynamics of land-use and land-cover change in tropical regions. *Annual Review of Environment and Resources,* **28**, 205-241.

Larcher W (2003) *Physiological Plant Ecology*. Springer-Verlag, 303pp

Lawless C, Semenov MA, Jamieson PD (2005) A wheat canopy model linking leaf area and phenology. *European Journal of Agronomy,* **22**, 19-32.

Lee B, Meneghin B, Turner M, Hoekstra T (2003) *An evaluation of landscape dynamic simulation models.* USDA Forest Service, 19 pp.

Leemans R (1989) *Description and simulation of stand structure and dynamics in some Swedish forests*. PhD thesis Uppsala University, Sweden, 89pp.

Leemans R (1994) The use of plant functional type classifications to model the global land cover and simulate the interactions between the terrestrial biosphere and the atmosphere. In: *Plant Functional Types Classifications* (eds. Smith TM, Shugart HH & Woodward FI), Cambridge University Press, Cambridge. pp 289-316

Leemans R, Cramer W, Van Minnen JG (1996) Prediction of global biome distribution using bioclimatic equilibrium models. In: *Effects of Global Change on Coniferous Forests and Grassland.* (eds. Melillo JM & Breymeyer A),. J. Wiley and Sons, New York. pp. 413-450

Leemans R, Eickhout B (2004) Another reason for concern: regional and global impacts on ecosystems for different levels of climate change. *Global Environmental Change,* **14**, 219-228.

Leemans R, Eickhout BJ, Strengers B, Bouwman AF, Schaeffer M (2002) The consequences for the terrestrial carbon cycle of uncertainties in land use, climate and vegetation responses in the IPCC SRES scenarios. *Science in China,* **43**, 1-15.

Leemans R, van den Born GJ (1994) Determining the potential global distribution of natural vegetation, crops and agricultural productivity. *Water, Air and Soil Pollution,* **76**, 133-162.

Leuning R, Kelliher FM, De Pury DGG, Schulze ED (1995) Leaf nitrogen, photosynthesis, conductance and transpiration: Scaling from leaves to canopy. *Plant, Cell and Environment,* **18**, 1183-1200.

Levin SA (1992) The problem of pattern and scale in ecology. *Ecology,* **73**, 1943-1967.

Levin SA (1993) Concepts of scale at the local level. In: *Scaling Physiological Processes: Leaf to Globe* (eds. Ehleringer JR & Field CB),. Academic Press, San Diego. pp. 7-19

Levy PE, Friend AD, White A, Cannell MGR (2004) The influence of land use change on global-scale fluxes of carbon from terrestrial ecosystems. *Climatic Change,* **67**, 185-209.

Li Z, Apps MJ, Kurz WA, Banfield E (2003) Temporal changes of forest net primary production and net ecosystem production in west central Canada associated with natural and anthropogenic disturbances. *Canadian Journal of Forestry Research,* **33**, 2340-2351.

Lieth H (1975) Primary production of the major vegetation units of the world. In: *Primary productivity of the biosphere* (eds. Lieth H & Whittaker RH), Springer-Verlag, Berlin. pp. 203-215.

Linder S (1987) Responses to water and nutrients in coniferous Ecosystems. In: (eds. Schulze ED & Zwolfer H), pp. 180-202

Lischke H, Löffler TJ, Fischlin A (1998) Aggregation of individual trees and patches in forest succession models - Capturing variability with height structured random dispersions. *Theoretical Population Biology,* **54**, 213-226.

Liski J, Karjalainen T, Pussinen A, Nabuurs GJ, Kauppi P (2000) Trees as carbon sinks and sources in the European Union. *Environmental Science and Policy,* **3**, 91-97.

Liski J, Korotkov A, Prins CFL, Karjalainen T, Victor DG, Kauppi PE (2003) Increased carbon sink in temperature and boreal forests. *Climatic Change,* **61**, 89-99.

Lloyd J, J. G, Miranda AC, Meir P, Wong SC, Miranda HS, Wright IR, Gash JHC, McIyre J (1995) A simple calibrated model of Amazon rainforest productivity based on leaf biochemical properties. *Plant, Cell and Environment,* **18**, 1129-1145.

Lloyd J, Taylor JA (1994) On the temperature dependence of soil respiration. *Functional Ecology,* **8**, 315-323.

Logofet DO, Lesnaya EV (2000) The mathematics of Markov models: What Markov chains can really predict in forest succession. *Ecological Modelling,* **126**, 285-298.

Loveland TR, Reed BC, Brown JF, D.O. O, Zhu Z, Yang L, Merchant JW (2000) Development of a global land cover characteristics database and IGBP DISCover from 1 km AVHRR data. *International Journal of Remote Sensing,* **21**, 1303-1330.

Lucht W, Schaphoff S, Erbrecht T, Heyder U, Cramer W (2006) Terrestrial vegetation redistribution and carbon balance under climate change. *Carbon Balance and Management,* **1:6 doi:10.1186/1750-0680-1-6**,

Lugo A (1997) An apparent paradox of re-establishing species richness on degraded lands with tree monocultures. *Forest Ecology and Management,* **99**, 9-19.

Lynch JA, Hollis JL, Hu FS (2004) Climatic and landscape controls of the boreal forest fire regime: Holocene records from Alaska. *Journal of Ecology,* **92**, 477-489.

MA (2005) *Assessment Synthesis Report.* The Millenium Ecosystem Assessment on Biodiversity, 219 pp.

MA (2005) Dealing with Scales. In: *Ecosystems and Human Well-being: A Framework for Assessment*, The Millenium Ecosystem Assessment on Biodiversity pp. 107-147.

Makundi WP (1997) Global climate change mitigation and sustainable forest management: The challenge of monitoring and verification. *Mitigation and Adaptation Strategies for Global Change,* **2**, 133-155.

Mann ME (2002) Climate reconstruction: the value of multiple proxies. *Science*, **297**, 1481-1482.

Marland G, Boden TA (2000) Global, Regional, and National CO2 Emissions. In: *Trends: A Compendium of Data on Global Change*. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge.

Marland G, Pielke RA, Apps M, Avissar R, Betts RA, Davis KJ, Frumhoff PC, Jackson ST, Joyce LA, Kauppi P, Katzenberger J, MacDicken KG, Neilson RP, Niles JO, Niyogi S, Norby RJ, Pena N, Sampson N, Xuer Y (2003) The climatic impacts of land surface change and carbon management, and the implications for climate-change mitigation policy. *Climate Policy,* **3**, 149-157.

Marland G, Schlamadinger B (1997) Forests for carbon sequestration or fossil fuel substitution? A sensitivity analysis.' *Biomass and Bioenergy,* **13**, 389-397.

Marland G, Schlamadinger B (1999) The Kyoto protocol could make a difference for the optimal forest based CO2 mitigation strategy: Some results for GORCAM. *Environmental Science & Policy,* **2**, 111-124.

Martin P (1993) Vegetation response and feedbacks to climate: a review of models and processes. *Climate dynamics,* **8**, 201-210.

Masera OR, Garza-Caligaris JF, Kanninen M, Karjalainen T, Liski J, Nabuurs GJ, Pussinen A, Jong BHJd, Mohren GMJ (2003) Modeling carbon sequestration in afforestation, agroforestry and forest management projects: the CO2FIX V.2 approach. *Ecological Modelling,* **`164**, 177-199.

Matthews R, Nabuurs GJ, Alexeyev V, Birdsey R, Fischlin A, MacLaren JP, Marland G, Price D (1996) Evaluating the role of forest management and forest products in the carbon cycle. In: *Forest ecosystems, forest management and the global Carbon cycle* (eds. Apps M & Price D),. Springer, Heidelberg, pp. 293-301.

McCarl B, Schneider I (2000) Economic potential of biomass based fuels from forests and agricultural sources. IN Proceeding of Conference Sustainable Energy: New Challenges for Agriculture and Implications for Land Use, (Eds E. van Ierland, A. Oude Lansink and E. Schmieman), Wageningen, the Netherlands,

McGuire AD, Melillo JM, Kicklighter DW, Pan YD, Xiao XM, Helfrich JVK, Moore B, III, Vörösmarty CJ, Schloss AL (1997) Equilibrium responses of global net primary production and carbon storage to doubled atmospheric carbon dioxide: sensitivity to changes in vegetation nitrogen concentration. **11**, 173-189.

McGuire AD, Sitch S, Clein JS, Dargaville R, Esser G, Foley JA, Heimann M, Joos F, Kaplan J, Kicklighter DW, Meier RA, Melillo JM, Moore BI, Prentice IC, Ramankutty N, Recheneau T, Schloss A, Tian HQ, Williams LJ, Wittenberg U (2001) Carbon balance of the terrestrial biosphere in the 20th century: Analyses of the CO2, climate and land use effects with four process-based ecosystem models. *Global Biogeochemical Cycles,* **15**, 183-206.

McNaughton KG (1994) Effective stomatal and boundary-layer resistance of heterogeneous surfaces. *Plant, Cell, and Environment,* **17**, 1061-1068.

Meehl GA, Stocker TF (2007) Global Climate Projections. In: *Climate Change 2007: The Physical Science Basis* (eds. Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt K, Tignor MMB & Miller HL), Working Group 1 Contribution to the Fourth Assessment Report of the Intergovernmental Panell on Climate Change (IPCC), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA pp. 747-847

Melillo J, Prentice C, Schulze D, Farquhar G, Sala O (1996) *Terrestrial Ecosystems: responses to global environmental change and feedbacks to climate.* IPCC 2nd assessment report, WGII, Chapter 9.

Melillo JM (1985) Forest litter decomposition in relation to soil nitrogen dynamics and litter quality. *Ecology,* **66**, 266-275.

Melillo JM, Steudler PA, Aber JD, Newkirk K, Lux H, Bowles FP, Catricala C, Magill A, Ahrens T, Morrisseau S (2002) Soil Warming and Carbon-Cycle Feedbacks to the Climate System. **298**, 2173-2176.

Metz B, Berk M, Kok M, Van Minnen JG, De Moor A, Faber A (2001) How can the European Union contribute to a CoP-6 agreement? An overview for policy makers. *International Environmental Agreement: Politics, Law and Economics,* **1**, 167-185.

Meyer WB, Turner BL, II (1998) *Changes in land use and land cover: a global perspective*(eds). Cambridge University Press, Cambridge, 537 pp.

Milne R, van Oijen M (2005) A comparison of two modelling studies of environmental effects on forest carbon stocks across Europe. *Annals of Forest Science,* **62**, 911-923.

Mitchell BR (1993) *International Historical Statistics, The Americas: 1750- 1988.* MacMillan, Indianapolis, Ind., 817 pp.

Mitchell BR (1998) *International Historical Statistics, Africa, Asia & Oceania: 1750 - 1993.* MacMillan, Indianapolis, Ind., 1113 pp.

Mitchell BR (1998) *International Historical Statistics, Europe: 1750- 1993.* MacMillan, Indianapolis, Ind., 959 pp.

MNP (2006) *Integrated modelling of global environmental change. An overview of IMAGE 2.4.* Bouwman AF, Kram T & Klein Goldewijk K (eds). Netherlands Environmental Assessment Agency (MNP), Bilthoven, the Netherlands, 228 pp.

Mohren GMJ, Bartelink HH, Jansen JJ (1994) Contrasts between biologically based process models and management-oriented growth and yield models. *Forest Ecology and Management,* **69**, 350 pp

Mohren GMJ, Burkhart HE (1994) Contrasts between biologically-based process models and management-oriented growth and yield models. *Forest Ecology and Management,* **69**, 1-5.

Mohren GMJ, Kramer K, Sabaté S (1997) *Impacts of Global Change on Tree Physiology and Forest Ecosystems*. Kluwer Academic Publishers.372pp.

Mollicone D, Matteucci G, Köble R, Masci A, Chieso M, Smits PC (2003) A model-based approach for the estimation of carbon sinks in European Forests. In: *Fluxes in carbon, water and energy in European forests* (ed. Valentini R), pp. 179-206. Springer, Berlin.

Monnin E, Iendermühle A, Dallenbach A, Fluckiger J, Stauffer B (2004) Atmospheric CO_2 concentration over the last glacial termination. *Science,* **291**, 112-114.

Mooney HA, Drake BG, Luxmoore RJ, Oechel WC, Pitelka LF (1991) Predicting ecosystems responses to elevated CO2 concentrations. **41**, 96-104.

Mooney HA, Koch GW (1994) The impact of rising CO_2 concentrations on the terrestrial biosphere. *Ambio,* **23**, 74-76.

Moore AD (1993) Automatic model simplification: The generation of replacement sequences and their use in vegetation modelling. *Ecological Modelling,* **70**, 137-157.

Morita T, Robinson J, Adegbulugbe A, Alcamo J, Herbert D, La Rovere EL, Nakicenovic N, Pitcher H, Raskin P, Riahi K, Sankovski A, Sokolov V, Vries HJM, Dadi Z (2001) *Greenhouse Gas Emission Mitigation Scenarios and Implications.* IPCC Third Assessment Report on Climate Change, Cambridge University Press, London, New York, pp115-166

Mosier A (1998) Soil processes and global change. *Biology and Fertility of Soils,* **27**, 221-229.

Nabuurs GJ, Dolman AJ, Verkaik E, Kuikman PJ, van Diepen CA, Whitmore AP, Daamen WP, Oenema O, Kabat P, Mohren GMJ (2000) Article 3.3 and 3.4 of the Kyoto Protocol: consequences for industrialised countries' commitment, the monitoring needs, and possible side effects. *Environmental Science and Policy,* **3**, 123-134.

Nabuurs GJ, Dolman AJ, Verkaik E, Whitmore AP, Daamen WP, Oenema O, Kabat P, Mohren GMJ (1999) *Resolving issues on terrestrial biospheric sinks in the Kyoto protocol.* Bilthoven, 100 pp.

Nabuurs GJ, Mohren GMJ (1993) *Carbon fixation through forestry activities.* IBN-DLO Wageningen, the Netherlands report no 93/4.

Nabuurs GJ, Paivinen R, Schanz H (2001) Sustainable management regimes for Europe's forests-a projection with EFISCEN until 2050. *Forest Policy and Economics,* **3**, 155-173.

Nabuurs GJ, Paivinen R, Sikkema R, Mohren GMJ (1998) The role of European forests in the global carbon cycle- A review. *Biomass and Bioenergy,* **13**, 345-358.

Nakicenovic N, Alcamo J, Davis G, de Vries B, Fenhann J, Gaffin S, Gregory K, Grübler A, Jung TY, Kram T, Emilio la Rovere E, Michaelis L, Mori S, Morita T, Pepper W, Pitcher H, Price L, Riahi K, Roehrl A, Rogner H-H, Sankovski A, Schlesinger ME, Shukla PR, Smith S, Swart RJ, van Rooyen S, Victor N, Dadi Z (2000) *IPCC Special Report on Emissions Scenarios*(eds). Cambridge University Press, Cambridge, 599 pp.

Neilson R (1993) Transient ecotone response to climatic change: Some conceptual and modeling approaches. *Ecological Applications,* **3**, 385-395.

Neilson R, Drapek R (1998) Potentially complex biosphere responses to transient global warming. *Global Change Biology,* **4**, 505-521.

Neilson RP (1993) Vegetation redistribution - a possible biosphere source of CO_2 during climatic change. *Water Air and Soil Pollution,* **70**, 659-673.

Neilson RP, Running SW (1996) Global dynamic vegetation modelling: Coupling biogeochemistry and biogeography models. In: *Global Change and terresrial biosphere* (eds. Walker B & Steffen W), pp. 451-465. Cambridge University Press

Nemani RR, Keeling CD, Hashimoto H, Jolly WM, Piper SC, Tucker CJ, Myneni RB, Running SW (2003) Climate-Driven Increases in Global Terrestrial Net Primary Production from 1982 to 1999. *Science,* **300**, 1560-1563.

Nepstad DC, Verissimo A, Alencar A, Nobre C, Lima E, Lefebvre P, Schlesinger P, Potter C, Moutinho P, Mendoza E, Cochrane M, Brooks V (1999) Large-scale impoverishment of Amazonian forests by logging and fire. *Nature,* **398**, 505-508.

New MG, Hulme M, Jones PD (2000) Representing twentieth century space–time climate variability. Part II: Development of 1901–96 monthly grids of terrestrial surface climate. *Journal of Climate,* **13**, 2217-2238.

Nilsson S, Schopfhauser W (1995) The carbon-sequestration potential of a global afforestation program. *Climatic Change,* **30**, 267-293.

Noble IR, Scholes RJ (2000) Sinks and the Kyoto Protocol. *Climate Policy,* **1**, 5-25.

Norby RJ, DeLucia EH, Gielen B, Calfapietra C, Giardina CP, King JS, Ledford J, McCarthy HR, Moore DJP, Ceulemans R, Angelise PD, Finzij AC, Karnosky DF, Kubiske ME, Lukac M, Pregitzer KS, Scarascia-Mugnozza GE, Schlesinger WH, Oren R (2005) Forest response to elevated CO2 is conserved across a broad range of productivity. *PNAS,* **102**, 18052-18056.

Norman JM (1993) Scaling processes between leaf and canopy levels. In: *Scaling Physiological Processes: Leaf to Globe* (eds. Ehleringer JR & Field CB),. Academic Press, San Diego, pp. 41-76

Nosetto MD, Jobbagy EG, Paruelo JM (2005) Land-use change and water losses: the case of grassland afforestation across a soil textural gradient in central Argentina. *Global Change Biology,* **11**, 1101-1117.

Nowak RS, Elsswoth DS, Smith SD (2004) Functional responses of plants to elevated atmospheric CO2. Do photosynthetic and productivity data from FACE experiments support early predictions. *New Phytologist,* **162**, 253-280.

NRRPC (2004) *Measurement of carbon sequestration in small non-industrial forest plantations.* Northern Rivers Region Plantation Committee.

O'Neill RV (1988) Hierarchy theory and global change. In: *Scales and global change* (eds. Rosswall T, Woodmansee RG & Risser PG), John Wiley & Sons, Chichester. pp. 29-45.

Ojima DS, Dirks BOM, Glenn EP, Owensby CE, Scurlock JO (1993) Assessment of C budget for grasslands and drylands of the world. *Water Air and Soil Pollution,* **70**, 95-109.

Olson J, Watts JA, Allison LJ (1985) *Major World Ecosystem Complexes Ranked by Carbon in Live Vegetation: A Database.* Carbon Dioxide Information Center,.

Onigkeit J, Sonntag M, Alcamo J (2000) *Carbon Plantations in the IMAGE model- Model description and scenarios.* Center for Environmental Systems Research, University of Kassel, Germany, 41pp.

Papale D, Valentini R (2003) A new assessment of European forests carbon exchanges by eddy fluxes and artificial neural network spatialization. *Global Change Biology,* **9**, 525-535.

Parry M, Rosenzweig C, Iglesia A, Levermore M, Fischer G (2004) Effects of climate change on global food production under SRES emissions and socio-economic scenarios. *Global Environmental Change,* **14**, 53-67.

Parton WJ, Ojima DS, Schimel D (1994) Environmental change in grasslands: Assessment using models. *Climatic Change,* **28**, 111-141.

Parton WJ, Schimel DS, Ojima DS, Vernon Cole C (1994) A general model for soil organic matter dynamics: Sensitivity to litter chemistry, texture and management. In (RB Bryant and RW Arnold eds) *Quantitative modeling of soil forming processes*. SSSA Spec. Publ. 39. pp 137-167

Payn TW, Skinner MF, Thorn AJ, Scott J, Downs S, Chapman H (2000) Scaling up or scaling down: The use of foliage and soil information for optimising the phosphate of radiata pine. *Forest Ecology and Management,* **138**, 79-89.

Peng C (2000) Growth and yield models for uneven-aged stands: Past, present and future. *Forest Ecology and Management,* **132**, 259-279.

Perry GLW, Enright NJ (2006) Spatial modelling of vegetation change in dynamic landscapes: a review of methods and applications. *Progress in Physical Geography,* **30**, 47-72.

Petit JR, Jouzel J, Raynaud D, Barkov NI, Barnola J-M, Basile I, Bender M, Chappellaz J, Davis M, Delaygue G, Delmotte M, Kotlyakov VM, Legrand M, Lipenkov VY, Lorius C, Pepin L, Ritz C, Saltzman ES, Stievenard M (1999) Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. **399**, 429-436.

Phat NK, Knorr W, Kim S (2004) Appropriate measures for conservation of terrestrial carbon stocks - Analysis of trends of forest management in Southeast Asia. *Forest Ecology and Management,* **191**, 283-299.

Picard G, Woodward FI, Lomas MR, Pellenq J, Quegan S, Kennedy M (2005) Constraining the Sheffield dynamic global vegetation model using stream-flow measurements in the United Kingdom. *Global Change Biology,* **11**, 2196-2210.

Pitelka LF (1997) Plant migration and climate change. *American Scientist,* **85**, 464-473.

Polglase PJ, Wang YP (1992) Potential CO_2-enhanced Carbon Storage by the Terrestrial Biosphere. *Australian Journal of Botany,* **40**, 641-656.

Post WM, Pastor J (1996) LINKAGES-An individual-based forest ecosystem model. *Climatic Change,* **34**, 253-261.

Potter C, Klooster S, Steinbach M, Tan P-N, Kumar V, Shekhar S, Carvalho CRd (2004) Understanding global teleconnections of climate to regional model estimates of Amazon ecosystem carbon fluxes. *Global Change Biology,* **10**, 693-703.

Potter CS, Klooster S, Brooks V (1999) Interannual variability in terrestrial net primary production: Exploration of trends and controls on regional to global scales. *Ecosystems,* **2**, 36-48.

Prentice CI, Heinmann M, Sitch S (2000) The Carbon Balance Of The Terrestrial Biosphere: Ecosystem Models And Atmospheric Observations. *Ecological Applications,* **10**, 1553-1573.

Prentice I, Harrison S, Jolly D, Guiot J (1998) The climate and biomes of Europe at 6000 yr BP: Comparison of model simulations and pollen-based reconstructions. *Quaternary Science Review,* **17**, 659-668.

Prentice IC, Bartlein PJ, Webb TM, III (1991) Vegetation and climate change in eastern North America since the last glacial maximum. *Ecology*, **72**, 2038-2056.

Prentice IC, Cramer W, Harrison SP, Leemans R, Monserud RA, Solomon AM (1992) A global biome model based on plant physiology and dominance, soil properties and climate. *Journal of Biogeography,* **19**, 117-134.

Prentice IC, Farquah MJR, Farham MJR, Goulden ML, Heinmann M, Jaramillo VJ, Kherghi HS, Le Quere C, Scholes RJ, Wallance DWR (2001) The carbon cycle and atmospheric carbon dioxide. In: *Climate change 2001: The Scientific Basis; Contribution of working group I to the 3rd assessment report of the IPCC,* (eds. Houghton JT, Ding Y, Griggs DJ, Noguer M, Linden PJvd, Dai X, Maskell K & Johnson CA), Cambridge University Press, London & New York, pp. 193-237.

Ramankutty N, Foley JA (1998) Characterizing patterns of global land use: An analysis of global ropland data. *Global Biogeochemical Cycles,* **12**, 667-685.

Ramankutty N, Gibbs HK, Achard F, Defries R, Foley JA, Houghton RA (2007) Challenges to estimating carbon emissions from tropical deforestation. *Global Change Biology,* **13**, 51-66.

Ravindranath N, Somashekhar B (1995) Potential and Economics of Forestry Options for Carbon Sequestration in India. *Biomass and Bioenergy,* **8**, 323-336.

Rayner PJ, Scholze M, Knorr W, Kaminski T, Giering R, Widmann H (2005) Two decades of terrestrial carbon fluxes from a carbon cycle data assimilation system (CCDAS). *Journal of Biogechemical Cycles,* **19**, 1-20.

Richards JF (1990) Land transformation. In: *The earth as transformed by human action* (eds. Turner BL, Clark WC, Kates RW, Richards JF, Mathews JT & Meyer WB),. Cambridge University Press, Cambridge. pp. 163-178

Richards JF, Flint E (1994) *Historic land use and carbon estimates for South and Southeast Asia 1880-1980.* Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennesee, US, Data set NDP-046 CDIAC/ORNL .

Richards KR, Stokes C (2004) A review of forest carbon sequestration cost studies: A dozen years of research. *Climatic Change,* **63**, 1-48.

Rosenzweig C, Iglesias A, Fischer G, Liu Y, Baethen W, Jones W (1999) Wheat yield functions for analysis of land-use changes in China. *Environmental Modelling and Assessment,* **4**, 115-132.

Running SW, Hunt ER (1993) Generalization of a forest ecosystem process model for other biomes, BIOME-BGC, and an application for global-scale models. In: *Scaling Physiological Processes: Leaf to Globe* (eds. Ehleringer JR & Field CB), Academic Press, San Diego. pp. 141-158.

Sabine CL, Heimann M, Artaxo P, Bakker DCE, Chen C-TA, Field CB, Gruber N, Quere CL, Prinn RG, Richey JE, Lankao PR, Sathaye JA, Valentini R (2004) Current status and past trends of the global carbon cycle. In: *The global carbon cycle: Integrating humans, climate and the natural world* (eds. Field CB & Raupach MR), Island Press, Washington. pp. 17-44.

Samson JC, Apps MJ, Kurz WZ, Mair R (1995) *The structure and dynamics of the carbon Budget Model.* Northern Forestry Center, Edmonton, Canada.

Sarmiento JL, Hughes TMC, Stouffer RJ, Manabe S (1998) Simulated response of the ocean carbon cycle to anthropogenic climate warming. **393**, 245-249.

Sarmiento JL, Wofsy SC (1999) *A US carbon cycle science plan.* University Corporation for Atmospheric Research, Bolder, Colorado, USA, 78pp.

Sathaye J, Bouille D, Biswas D, Crabbe P, Geng L, Hall D, Imura H, Jaffe A, Michaelis L, Peszko G, Verbruggen A, Worrell E, Yamba F (2001) Barriers, Opportunities, and Market Potential of Technologies and Practices. In: *Climate change 2001: Mitigation, Contribution of working group III to the 3rd assessment report of the IPCC,* (eds. Metz B, Davidson O, Swart R & Pan J), IPCC, Cambridge University Press, London, New York. pp. 351 - 758.

Sathaye JA, Andrasko K, Markundi W, Lebre La Rovere E, Ravindranath NH, Melli A, Rangaschari A, Imaz M, Gay C, Friedmann R, Goldberg B, Van Horen C, Simmonds G, Garker G (1999) Concerns about climate change mitigation projects: Summary of findings from case studies in Brazil, India, Mexico and South Africa. *Environmental Science and Policy,* **2**, 187-198.

Sathaye JA, Markundi W, Andrasko K, Boer R, Ravindranath NH, Sudha P, Rao S, Lasco R, Pulhin F, Masera O, Ceron A, Ordonez J, Deying X, Zhang X, Zuomin S (2001) Carbon mitigation potential and costs of forestry options in Brazil, China, India, Indonesia, Mexico, the Philippines and Tanzania. *Mitigation and Adaptation Strategies for Global Change,* **6**, 185-211.

Sathaye JA, Markundi W, Dale L, Chan P, Andrasko K (2006) GHG mitigation potential, costs and benefits from global forests. *Energy Journal,* Special Issue 3

Sato H, Itoha A, Kohyama T (2007) SEIB–DGVM: A new Dynamic Global Vegetation Model using a spatially explicit individual-based approach. *Ecological Modelling,* **200**, 279-307.

Schaeffer M, Eickhout B, Hoogwijk M, Strengers B, Van Vuuren D, Leemans R, Opsteegh T (2006) CO_2 and albedo climate impacts of extratropical carbon and biomass plantations. *Global Biogeochemical Cycles,* **20**, GB2020, doi 10-1029/2005GB002581.

Schaphoff S, Lucht W, Gerten D, Sitch S, Cramer W, Prentice CI (2006) Terrestrial biosphere carbon storage under alternative climate projections. *Climatic Change,* **74**, 97-122.

Schär C, Jendritzky G (2004) Climate change: Hot news from summer 2003. **432**, 559-560.

Scheffer M, Brovkin V, Cox PM (2006) Positive feedback between global warming and atmospheric CO2 concentration inferred from past climate change. *Geophysical Research Letters,* **33**, L10702, doi:10.1029/2005GL025044.

Schellnhuber HJ, Cramer W, Nakicenovic N, Wigley T, Yohe G (2006) *Avoiding Dangerous Climate Change*(eds). Cambridge University Press, Cambridge, UK, 406 pp.

Schimel DS, Melillo JE, Tian H, McGuire AD, Kicklighter D, Kittel T, Rosenbloom N, Running S, Thornton P, Ojima D, Parton W, Kelly R, Sykes M, Neilson R, Rizzo B (2000) Contribution of increasing CO2 and climate to carbon storage by ecosystems in the United States. *Science,* **287**, 2004-2006.

Schlamadinger B, Marland G (1998) The Kyoto Protocol: Provision and unresolved issues relevant to land-use change and forestry. *Environmental Science and Policy,* **1**, 313-327.

Schlamadinger B, Marland G (2000) *Forests, land management and the Kyoto Protocol.* Pew Center on Global Climate Change, Pew Center on Global Climate Change Arlington, USA, 63 pp.

Schlesinger WH (2000) Carbon sequestration in soils: Some cautions amidst optimism. *Agriculture, Ecosystems and Environment,* **82**, 127-127.

Schlesinger WH, Lichter J (2001) Limited carbon storage in soil and litter of experimental forest plots under increased atmospheric CO2. *Nature,* **411**, 466-469.

Schober R (1975) *Ertragstafeln wichtiger Baumarten*. J.D. Sauerlander Verlag, Frankfurt a.M., 154p.

Scholes RJ, Noble IR (2001) Storing Carbon on Land. *Science,* **294**, 1012-1013.

Seino H, Uchijima Z (1992) Global Distribution of Net Primary Productivity of Terrestrial Vegetation. *Journal of Agricultural Meterology,* **48**, 39-48.

Sellers PJ, Randall DA, Collatz GJ, Berry JA, Field CB, Dazlich DA, Zhang C, Collelo GD, Bounoua L (1996) A revised land surface parameterization (SiB2) for atmospheric GCMs. Part I: Model formulation. *Journal of Climate,* **9**, 676-705.

Shaver GR, Giblin AE, Nadelhoffer KJ, Thieler KK, Downs MR, Laundre JA, Rastetter EB (2006) Carbon turnover in Alaskan tundra soils: effects of organic matter quality, temperature, moisture and fertilizer. *Journal of Ecology,* **94**, 740-753.

Shugart HH, Smith TM (1996) A review of forest patch models and their application to global change research. *Climatic Change,* **34**, 131-153.

Shugart HH, West DC, Emanuel WR (1981) Patterns and Dynamics of forests: an application of simulation models. In: *Forest Succession. Concepts and Application* (eds. West DC, Shugart HH & Botkin DB),. Springer-Verlag, New York. pp. 74-106

Siegenthaler U, Stocker TF, Monnin E, Luthi D (2005) Stable carbon cyle climate relationship during the later Peistocene. *Science,* **310**, 1313-1317.

Silver WL (1998) The potential effects of elevated CO2 and climate change on tropical forest soils and biogeochemical cycling. *Climatic Change,* **39**, 337-361.

Silver WL, Ostertag R, Lugo AE (2000) The potential for carbon sequestration though reforestation of abandoned tropical agricultural and pasture lands. *Restoration Ecology,* **8**, 394-407.

Sitch S, Cox PM, Collins WJ, Huntingford C (2007) Indirect radiative forcing of climate change through ozone effects on the land-carbon sink. *Nature*, **448**, 791-795

Sitch S, Brovkin V, Von Bloh W, van Vuren DP, Eickhout B, Ganopolski A (2005) Impacts of future land cover changes on atmospheric CO2 and climate. *Global Biogeochemical Cycles,* **19**, 1-15.

Sitch S, Smith B, Prentice IC, Arneth A, Bondeau A, Cramer W, Kaplan JO, Levis S, Lucht W, Sykes MT, Thonicke K, Venevski S (2003) Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ Dynamic Global Vegetation Model. *Global Change Biology,* **9**, 161-185.

Smith P, Andren O, Brussaard L, Dangerfield M, Ekschmitt K, Lavelle P, Tate K (1998) Soil biota and global change at the ecosystem level: describing soil biota in mathematical models. *Global Change Biology,* **4**, 773-784.

Smith TM, Cramer WP, Dixon RK, Leemans R, Neilson RP, Solomon AM (1993) The global terrestrial carbon cycle. *Water Air and Soil Pollution,* **70**, 19-37.

Smith TM, Leemans R, Shugart HH (1992) Sensitivity of terrestrial carbon storage to CO_2 induced climate change: Comparison of four scenarios based on general circulation models. *Climatic Change,* **21**, 367-384.

Smith TM, Shugart HH (1993) The transient response of terrestrial carbon storage to a perturbed climate. *Nature,* **361**, 523-526.

Sohngen B, Mendesohn R (2003) An Optimal Control Model of Forest Carbon Sequestration. *American Journal of Agricultural Economics,* **85**, 448-457.

Sohngen B, Sedjo RJ (2006) Carbon sequestration costs in global forests. *Energy Journal,* Special Issue 3,

Solomon AM, Leemans R (1997) Boreal forest carbon stocks and wood supply: Present and future responses to changing climate, agriculture and species availability. *Agricultural and Forest Meteorology,* **84**, 137-151.

Solomon AM, West DC, Solomon JA (1981) Simulating the role of climate change and species immigration in forest succession. In: *Forest Succession. Concepts and Application* (eds. West DC, Shugart HH & Botkin DB), pp. 154-177. Springer-Verlag, New York.

Sonntag M (1997) Comparison of forest models at the leaf and canopy scale. In: *Impacts of Global Change on Tree Physiology and Forest Ecosystems* (eds. Mohren GMJ, Kramer K & Sabaté S), Kluwer Academic Publishers pp. 299-306.

Sonntag M (1998) *Klimaveränderung und Waldwachstum: TREEDYN3-Simulationen mit einer Analyse modellstruktureller unsicherheiten*. PhD thesis. Kassel University, Germany.

Steffen W, Noble I, Canadell J, Apps M, Schulze ED, Jarvis PG, Baldocchi D, Ciais P, Cramer W, Ehleringer J, Farquhar G, Field CB, Ghazi A, Gifford R, Heimann M, Houghton R, Kabat P, Körner C, Lambin E, Linder S, Mooney HA, Murdiyarso D, Post WM, Prentice IC, Raupach MR, Schimel DS, Shvidenko A, Valentini. R (1998) The Terrestrial Carbon Cycle: Implications for the Kyoto Protocol. *Science,* **280**, 1393-1394.

Stephens BB, Gurney KR, Tans PP, Sweeney C, Peters W, Bruhwiler L, Ciais P, Ramonet M, Bousquet P, Nakazawa T, Aoki S, Machida T, Inoue G, Vinnichenko N, Lloyd J, Jordan A, Heimann M, Shibistova O, Langenfelds RL, Steele LP, Francey RJ, Denning AS (2007) Weak Northern and Strong Tropical Land Carbon Uptake from Vertical Profiles of Atmospheric CO2. *Science,* **316**, 1732-1735.

Stinson G, Freenman B (2001) Potential for carbon sequestration in Canadian forests and agroecosystems. *Mitigation and adaptation strategies for global change,* **6**, 1-23.

Strengers B, van Minnen JG, Eickhout B (2007) The costs and uncertainties in establishing C plantations in order to mitigate climate change. *Climatic Change,* **in press**,

Sykes MT, Prentice IC (1995) Boreal Forests futures: Modelling the controls on tree species range limits and transient responses to climate change. *Water, Air and Soil Pollution,* **82**, 415-428.

Tian HQ, Melillo JM, Kicklighter DW, McGuire AD, Helfrich JVK (1999) The sensitivity of terrestrial carbon storage to historical climate variability and atmospheric CO_2 in the United States. Tellus B, **51**, 414-452.

Tiktak A, Van Grinsven JJM (1995) Review of sixteen forest-soil-atmosphere models. *Ecological Modelling,* **83**, 35-53.

Torfs PJJF (1996) Schaal relaties in hydrologie. Proceedings Workshop *Scaling biogeochemical processes in space and time*, Wageningen,.6pp ..

Trenberth KE, Jones PD (2007) Observations: Surface and atmospheric climate change. In: *Climate Change 2007: The Physical Science Basis* (eds. Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt K, Tignor MMB & Miller HL). Working Group 1 Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Tubiello FN, Amthor JA, Boote K, Donatelli M, Easterling WE, Fisher G, Gifford R, Howden M, Reilly J, Rosenzweig C (2007) Simulating the effects of elevated CO2 on crops: approaches and applications for climate change. *European Journal of Agronomy,* **26**, 215-223.

Tubiello FN, Ewert F (2002) Simulating the effects of elevated CO2 on crops: approaches and applications for climate change. *European Journal of Agronomy,* **18**, 57-74.

Tunctaner K (2004) *Sustainability of industrial forest plantations in Turkey.* University of Zonguldak Kararaelmas, Faculty of Forestry, 19 pp.

UN-ECE/FAO (2000) *Forest resources of Europe, CIS, North America, Australia, Japan and New Zealand.* United Nations Economic Commission for Europe, Geneva, .

UNDP (2000) *World Energy Assessment.* World Energy Council, United Nations Department of Economics and Social Affairs, New York, USA, .

UNFCCC (1993) *The United Framework Convention on Climate Change.* UN, .

UNFCCC (2001) *Document on the Implementation of the Buenos Aires Plan for Action.* UNFCCC secretariat, Bonn, .

Valentini R, Matteucci G, Dolman AJ, Schulze E-D, Rebmann C, Moors EJ, Granier A, Gross P, Jensen NO, Pilegaard K, Lindroth A, Grelle A, Bernhofer C, Grünwald T, Aubinet M, Ceulemans R, Kowalski AS, Vesala T, Rannik U, Berbigier P, Loustau D, Guomundson J, Thorgeirsson H, Ibrom A, Morgenstern K, Climent R, Moncrieff J, Montagnai L, Minerbi S, Jarvis PG (2000) Respiration as the main determinant of carbon balance in European forests. *Nature,* **404**, 861-865.

Van de Hoef L, Hill B (2003) *Radiata pine for farm forestry.* NRE, 2pp.

Van Heerden K, Van Grinsven JJM, Tiktak A (1995) Simulation of forest stress to the Solling spruce site with SOILVEG. *Ecological Modelling,* **83**, 185-195.

Van Laar HH, Van Keulen H, Goudriaan J (1992) *Simulation of crop growth for potential and water-limited production situations, as applied to spring wheat.* Agricultural University, Wageningen, the Netherlands, 72 pp.

Van Minnen JG, Klein Goldewijk K, Eickhout B, Stehfest E, Van Drecht G, Leemans R (2008) The importance of three centuries of climate and land-use change for the global and regional terrestrial carbon cycle. *Climatic Change,* **submitted**,

Van Minnen JG, Klein Goldewijk K, Leemans R (1995) The importance of feedback processes and vegetation transition in the terrestrial carbon cycle. *Journal of Biogeography,* **22**, 805-814.

Van Minnen JG, Klein Goldewijk K, Leemans R, Kreileman GJJ (1996) *Documentation of a geographically explicit dynamic carbon-cycle model.* RIVM, 83pp.

Van Minnen JG, Leemans R, Ihle F (2000) Assessing consequences of dynamic changes in global vegetation patterns, using the IMAGE 2.1 model. *Global Change Biology,* **6**, 595-611.

Van Minnen JG, Meijers R, Braat LC (1995) Application of the FORSOL model to the spruce site at Solling, Germany. *Ecological Modelling,* **83**, 197-205.

Van Minnen JG, Strengers B, Eickhout B, Klein Goldewijk K (2006) Simulating carbon exchange between the terrestrial biopshere and atmosphere. In: *Integrated modelling of global environmental change.* in Bouwman AF, Kram, T., and Klein Goldewijk, K.(eds), *An overview of IMAGE 2.4* Netherlands Environmental Assessment Agency, Bilthoven, pp. 113-130.

Van Vuuren D, Den Elzen M, Lucas P, Eickhout B, Strengers B, Van Ruijven B, Wonink S, Van den Houdt R (2007) Stabilizing greenhouse gas concentrations at low levels. An assessment of reduction strategies and costs. *Climatic Change,* **81**, 119-159.

Van Vuuren D, Den Elzen M, Lucas P, Eickhout B, Strengers B, Van Ruijven B, Wonink S, Van den Houdt R, Berk M, Oostenrijk R (2007) Stabilising greenhouse gas concentrations. Assessment of different strategies and costs using an integrated assessment framework. *Climatic Change,* a**ccep**,

Van Vuuren DP, Van Ruijven B, Hoogwijk M, Isaac M, De Vries HJM (2006) TIMER 2: Model description and application. In: *Integrated modelling of global environmental change. An overview of IMAGE 2.4* (ed. MNP (Bouwman AF, Kram, T., and Klein Goldewijk, K.)), pp. 38-61. Netherlands Environmental Assessment Agency, Bilthoven.

Vanclay JK, Skovsgaard JP (1997) Evaluating forest growth models. *Ecological Modelling,* **98**, 1-12.

Venevsky SV (1994) *A set of biogechemical models. Approaches for integrated modeling of climate change impacts. Biospheric carbon and nitrogen cycles.* International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria, 25 pp.

Verboom J (1996) *Modeling fragmented populations: Between theory and application in landscape planning*. PhD, University of Leiden, 119p.

Vrolijk C, Grubb M, Metz B, Haites E (2000) Quantifying Kyoto Workshop. A summary. Royal Institute of International Affairs, London, http://www.riia.org/research.

Walther GR, Post E, Convey P, Menzel A, Parmesan C, Beebee TJC, Fromentin JM, Hoegh Guldberg O, Bairlein F (2002) Ecological responses to recent climate change. *Nature,* **416**, 389-395.

Waring R, Running S (1998) *Forest Ecosystems. Analysis at multiple scales*. Academic Press, San Diego.370.

Waring RH, Schlesinger WH (1985) *Forest Ecosystems. Concepts and Management*. Academic Press, Orlando.340.

Watson AJ, Bakker DCE, Ridgwell AJ, Boyd PW, Law CS (2000) Effect of iron supply on Southern Ocean CO2 uptake and implications for glacial atmospheric CO2. *Nature,* **407**, 730-733.

Watson RT, Noble IR, Bolin B, Ravindranth NH, Verado D, Dokken DJ (2000) *IPCC Special report on Land Use, Land-Use Change, and Forestry*. Cambridge University Press, Cambridge, 377 pp.

WBGU (1998) *The accounting of biological sinks and sources Under the Kyoto Protocol: a step forwards or backwards for global environmental protection?* German Advisory Council on Global Change, Berlin.85pp.

Wofsy SC (2001) Where has all the carbon gone? *Science,* **292**, 2261-2263

Woodward FI (1987) *Climate and Plant Distribution*. Cambridge University Press, Cambridge.174.

Woodward FI, Kelly CK (1997) Plant functional types: Towards a definition by environmental constraints. In: *Plant Functional Types* (eds. Smith TM, Shugart HH & Woodward FI), pp. 47-65. Cambridge University Press, Cambridge.

Woodward FI, Lomas MR (2004) Vegetation dynamics - simulating responses to climatic change. *Biological Reviews,* **79**, 643-670.

Woodward FI, Smith TM, Emanuel WR (1995) A global land primary productivity and phytogeography model. *Global Biogeochemical Cycles,* **9**, 471-490.

WRI (1991) *World Recource, 1990-1991.* World Resources Institute, the United Nations Environment Programme, Washington,

Wu J, Jenerette GD, David JL (2003) Linking Land-use Change with Ecosystem Processes: A Hierarchical Patch Dynamic Model. In: *Integrated land Use and Environmental Models* (ed. Guhathakurta S),. Springer, Berlin pp. 99-119.

Zaehle S, Sitch S, Smith B, Hatterman F (2005) Effects of parameter uncertainties on the modeling of terrestrial biosphere dynamics. *Global Biogeochemical Cycles,* **19**, 16. doi:10.1029/2004GB002395

Papers in peer-reviewed journals & books

Strengers B, van Minnen JG, Eickhout B (2007) The costs and uncertainties in establishing C plantations in order to mitigate climate change. *Climatic Change,* **in press**,

Van Minnen JG, Eickhout B, Strengers BJ, Brinkman S, Van den Houd R, Leemans R (2007) The consequences of uncertainties in the vegetation response to climate change on the global and regional terrestrial C cycle. *Ecological Modelling,* **submit.**[1],

Van Minnen JG, Klein Goldewijk K, Eickhout B, Stehfest E, Van Drecht G, Leemans R (2007) The importance of three centuries of climate and land-use change for the global and regional terrestrial carbon cycle. *Climatic Change,* **submit,**[1]

Van Minnen JG, Strengers BJ, Eickhout B (2007) Evaluating the role of carbon plantations in climate change mitigation including land-use requirements. *Carbon Balance and Management,* **submit.** [1],

Füssel HM, Toth FL, Van Minnen JG, Kaspar F (2003) Climate impact response functions as impact tools in the tolerable windows approach. *Climatic Change,* **56**, 91-117.

Van Minnen JG, Van Ierland E, Nabuurs G (2003) Terrestrial carbon sinks and biomass in international climate policies. In Van Ierland E, Gupta J & Kok MTJ (eds): *Issues in International Climate Policy. Theory and policy*, Edward Elgar Press, pp 137-168 [1]

Alcamo J, Mayerhofer P, Guardans R, Van Harmelen T, Van Minnen JG, Onigkeit J, Posch M, De Vries HJM (2002) An integrated Assessment of Regional Air Pollution and Climate Change in Europe: Findings of the AIR-CLIM project. *Environmental Science and Policy,* **5**, 257-272.

Metz B, Mol A, Andersson M, Berk M, Van Minnen JG, Tuinstra W (2002) Climate Options for the long term: Possible strategies. In Van Ierland E, Gupta J & Kok MTJ (eds): *Issues in International Climate Policy. Theory and policy*, Edward Elgar Press, 263-284,

Van Minnen JG, Onigkeit J, Alcamo J (2002) Critical climate change as an approach to assess climate change impacts in Europe: development and application. *Environmental Science and Policy,* **5**, 335-347.

Füssel HM, Van Minnen JG (2001) Climate impact response functions for terrestrial ecosystems. *Integrated Assessment,* **2**, 183-197.

Mayerhofer P, Alcamo J, Posch M, Van Minnen JG (2001) Regional Air pollution and climate change in Europe: An integrated assessment (AIR-CLIM). *Water, Air and Soil Pollution,* **130** 1151-1156.

Metz B, Berk M, Kok M, Van Minnen JG, De Moor A, Faber A (2001) How can the European Union contribute to a CoP-6 agreement? An overview for policy makers. *International Environmental Agreement: Politics, Law and Economics,* **1**, 167-185.

Van Minnen JG, Alcamo J, Haupt W (2000) Deriving and applying response surface diagrams for evaluating climate change impacts on crop yield. *Climatic Change,* **46**, 317-338.

Van Minnen JG, Leemans R, Ihle F (2000) Assessing consequences of dynamic changes in global vegetation patterns, using the IMAGE 2.1 model. *Global Change Biology,* **6**, 595-611 [1].

Alcamo J, Kreileman GJJ, Krol M, Leemans R, Bollen J, Van Minnen JG, Schaefer F, Toet S, De Vries B (1998) Global modelling of environmental change: An overview of IMAGE 2.1. In Alcamo J, Leemans R & Kreileman GJJ (eds): *Global change scenarios of the 21st century. Results from the IMAGE 2.1 model*, Pergamon Press/Elsevier Science, London. pp 3-94.

Leemans R, Cramer W, Van Minnen JG (1996) Prediction of global biome distribution using bioclimatic equilibrium models. In Melillo JM & Breymeyer A (eds.): *Effects of Global Change on Coniferous Forests and Grassland.* J. Wiley and Sons, New York. pp. 413-450.

Alcamo J, Battjes C, Van der Born GJ, Bouwman AF, De Haan BJ, Klein Goldewijk K, Klepper O, Kreileman GJJ, Krol M, Leemans R, Van Minnen JG, Olivier JGJ, De Vries HJM, Toet AMC, Van den Wijngaart RA, Van der Woerd HJ, Zuidema G (1995) Overview of IMAGE 2.0: An integrated model of climate change and the global environment. In: *Climate change research. Evaluation and policy implications* (eds. Zwerver S, Van Rompaey RSAR, Kok MTJ & Berk MM),. Elsevier pp. 1395-1399

Heil GW, Aerts JJH, Van Boxtel AMJV, Van Deursen WPA, Leemans R, Van Minnen JG (1995) Remote sensing based modeling of the terrestrial carbon cycle in Europe. In Zwerver S, Van Rompaey RSAR, Kok MTJ & Berk MM (eds.): *Climate change research. Evaluation and policy implications* Elsevier, Amsterdam, pp 567-570.

Van Minnen JG, Klein Goldewijk K, Leemans R (1995) The importance of feedback processes and vegetation transition in the terrestrial carbon cycle. *Journal of Biogeography,* **22**, 805-814 [1].

Van Minnen JG, Meijers R, Braat LC (1995) Application of the FORSOL model to the spruce site at Solling, Germany. *Ecological Modelling,* **83**, 197-205.

Bakema AH, De Boer KF, Braat LC, Kok RM, Meijers R, Van Minnen JG (1994) EXPECT: A concise simulation system for environmental policy analysis. *Ecological Modelling,* **75/76**, 553-561.

Klein Goldewijk K, Van Minnen JG, Kreileman GJJ, Vloedbeld M, Leemans R (1994) Simulation of the carbon flux between the terrestrial environment and the atmosphere. *Water, Air and Soil Pollution,* **76**, 199-230 [1].

Tiktak A, Bakema AH, De Boer KF, Erisman JW, Van Grinsven JJM, Van Heerden K, Heij GJ, Kros J, De Leeuw FAAM, Van Minnen JG, Van der Salm C, Voodg JCH, De Vries W (1992) Scenario analysis with the Dutch Acidification System (DAS) model: An example for forests and forest soils. In Schneider T (ed.): *Acidification Research: Evaluation and policy applications*; Elseviers, Amsterdam; pp 319-340

---

[1] Used in this thesis

Summary

Context

The earth's climate is changing, with even more changes projected for the coming centuries. Up to the year 2100, for example global temperature may rise by 1.8 to 4.0 °C in comparison to the 1980–2000 average (best estimate, likely range 1.1–6.4 °C), and more frequent and intense extreme weather events may occur. The ongoing climate change has caused considerable impacts on nature, human health, and society. These impacts are expected to become more pronounced in the coming decades and centuries. Note that not all current and projected effects of climate change are adverse. The agricultural sector in some parts of Europe, for example, may benefit from a (limited) temperature rise.

Gradually, we have come to realize that although the observed climatic changes are to some extent the result of natural causes (e.g. volcanoes and sun activity), most are very likely attributable to the increased concentrations of greenhouse gases (GHG) in the atmosphere. Substantial reductions in GHG emissions are needed if the impacts of climate change are to be kept within manageable levels. To determine the required long-term emission reductions, a thorough understanding of the global C cycle is needed. The C cycle consists of three major interacting compartments: the atmosphere, the oceans, and the terrestrial biosphere Understanding the three compartments and their interactions is relevant, because, for example, at the moment the terrestrial biosphere and ocean sequester about 55% of the emitted $CO_{2,}$ thus slowing down the atmospheric CO_2 increase. However, future sequestration is uncertain. A general decrease would imply more stringent emission reduction measures to achieve the stabilization of GHG concentrations in the atmosphere.

The terrestrial biosphere affects the C cycle in the following ways: (i) through the substantial contribution of land-use changes to the atmospheric CO_2 increase; (ii) through the sequestering of carbon by the remaining natural biosphere, which slows down the increase in atmospheric CO_2 concentration; (iii) through the acceptance in the policy arena of the protection and establishment of forests as mitigation measure. The terrestrial C cycle consists of many physical, chemical, and biological processes that operate on different scales, and that interact and respond quickly to environmental and anthropogenic changes. The complex structure and dynamics in time and space lead to considerable uncertainty in projecting the future behavior of the terrestrial C cycle.

Developing a more robust understanding of the role of the many processes involved in the terrestrial C cycle and their interactions can, for example, be based on use of simulation models. Simulation models have proven to be powerful tools for analyzing the consequences of different assumptions for the C cycle, and of various parameter settings and scenarios. The terrestrial C-cycle model of IMAGE 2 (Integrated Model for Assessing the Global Environment) forms the backbone of this thesis. IMAGE 2

is an integrated approach that includes both socio-economic (i.e. land and energy use) and natural (biogeographical and biogeochemical processes) dimensions with their interactions and feedbacks. Changes in land use comprehensively include deforestation for cropland and pasture expansion, timber harvesting, and reforestation.
The main research objective of this thesis is *to assess the response of the terrestrial biosphere to changing environmental conditions and land use, and the consequences for the global and regional C cycle*. To achieve this, the IMAGE-2 C-cycle model is described in detail, and is applied to the past three centuries as well as various scenarios up to 2100. Furthermore the model is used in assessing uncertainties of relevant processes. The position of the IMAGE-2 C-cycle model is also discussed in a broader context by comparing the model's results with observed trends, and comparing the model's algorithm and results with other C-cycle models. These models range from highly aggregated and simple, to complex and process-based. All of these activities have contributed to provide answers to the five main research questions, described and answered below. Finally, the main conclusions are summarized.

Results and discussion

1. *What are the main processes that determine the role of the terrestrial biosphere in the C cycle on global and regional scales?*

This thesis shows that the terrestrial biosphere plays a crucial role in the global C cycle on time scales ranging from months/seasons to centuries. The biosphere stores large quantities of carbon and exchanges considerable amounts with the atmosphere at fast rates. On longer time scales, the ocean exchange becomes more dominant. Oceans store by far the largest amount of C, but since C is relatively inert, it will be less relevant for changes in the C cycle over the coming decades.

The role of the biosphere in the global C cycle is determined by many biogeochemical, biophysical, ecological and anthropogenic (i.e. land-use) processes. Important biogeochemical processes are net primary production (NPP), soil respiration and disturbances. All these processes interact in multiple ways and are affected by changing environmental conditions. The relevance of the individual processes in the C cycle also depends on the temporal and spatial scales considered. When analyzing biogeochemical feedbacks, for example, a robust finding of many studies – including this thesis – is that the most important process globally is CO_2 fertilization (i.e. the physiological response to increasing CO_2 levels in the atmosphere). Ignoring this effect has larger consequences for C fluxes and pools than uncertainties in future land use do. Regionally, there are differences: CO_2 fertilization and the climate effect on soil respiration are the most relevant in tropical regions, whereas in boreal regions, the NPP response to temperature, along with CO_2 fertilization, determine the C pools and fluxes. Likewise, land-use changes related to crop and pasture expansion currently have major impacts on the C cycle in tropical regions, whereas wood harvest is especially relevant for the C cycle in temperate regions.

The understanding of the terrestrial C cycle has significantly improved in recent decades thanks to a combination of laboratory and field experiments, satellite observations and modeling exercises. As a result, the present-day ranges in estimated global C pools and fluxes have decreased. Estimates of the global NPP in the 1980s and 1990s, for example, ranged from 45 to 68 Pg C.yr^{-1}. More recent studies show ranges from 55 to 63 Pg C.yr^{-1} (while this study provides a range of 58 to 61 Pg C.yr^{-1}). Likewise, projections on the future role of the biosphere have become more consistent. Many modeling studies have shown the terrestrial C storage in the next decade to increase, followed by a decrease towards the end of the 21st century. However, regionally – especially in tropical regions – the differences among studies are still considerable. This is caused by using different measurement methods, definitions, and time periods.

2. *What are the consequences of past and future changes in climate and land use on the regional and global terrestrial C cycle?*

This thesis provides new estimates on past, current, and future C fluxes – both global and regional – from land use and natural ecosystems. The historical estimates are based on an analysis using both IMAGE 2 (version 2.4) and the HYDE dataset of historical land-use reconstruction. For the projections, the most sensitive parameters of the IMAGE-2 model (version 2.3) were identified using a sensitivity analysis. IMAGE 2 has been used to integrate ecosystem and land-use (i.e. agriculture and forestry) related carbon dynamics with fluxes from energy use and ocean atmospheric dimensions. HYDE is a global dataset for land-use reconstruction used to allocate historical cropland and pasture.

On the basis of these simulations, I conclude that for the past centuries, land use has had a more important role in the global and regional C cycle than natural processes. Net, land-use changes and the natural processes emitted 35 Pg C to the atmosphere throughout the 1700-2000 period. If land use had remained constant at its distribution in 1700, the estimated terrestrial C storage would have increased by 142 Pg C. This overall difference in terrestrial C storage of 177 Pg C is more than half the historical fossil fuel-related emissions of 308 Pg C. Up to 1900 land-use emissions were even estimated to be dominant over energy emissions. In past decades the relative importance of land use has decreased due to lower land-use emissions (e.g. 1.3 Pg C yr^{-1} for the 1990s) and accelerating environmental change (e.g. climate, CO_2, and nitrogen deposition), which is rapidly altering the terrestrial ecosystems and their C fluxes. The global NPP flux, for example, increased from about 52 Pg C yr^{-1} in 1700 up to about 60 Pg C yr^{-1} in 2000. Similar, the NEP was estimated at close to zero up to the early 20th century, followed by an increase of up to 2.1 Pg C yr^{-1} for the 1990s.

The historical roles of land use and natural processes have varied geographically. In Europe and especially the USA, land-use change played an important role at the end of 19th, and early 20th century, resulting in considerable C emissions. This trend changed around 1950, because agricultural abandonment led to afforestation. Nowadays, both the land use and natural fluxes in these regions are a considerably lower than energy- and industry-related emissions. Most tropical regions are estimated to have been about C-neutral prior to 1950. The accelerated deforestation since 1950 has resulted in considerable loss of natural ecosystems and associated CO_2 emissions and lower natural C uptake rates. Thus these regions have now become major C sources. Although energy and industry-related emissions are currently also increasing in many tropical regions, in several countries they are generally still lower than the land-use emissions. Avoiding future land-use changes in these regions would effectively limit further increase of atmospheric CO_2. However, given the importance of the energy sector, climate policies that focus solely on slowing down deforestation or enhancing afforestation will not be sufficient to mitigate all climate change.

Land use and natural processes are also projected as being important for the future global and regional C cycle. The historically important (sometimes even dominant) role of land use in the terrestrial C cycle is projected to decrease. This is because the biosphere C uptake changes more than the land-use emissions due to substantial responses to the changes in climate and CO_2. Global land-use emissions are, however, projected to increase in all scenarios up to about 2050 (with a maximum of 2.7 Pg C yr^{1} in the IPCC SRES A1b baseline scenario). Beyond 2050, the emissions vary among the scenarios, from a continuous increase in the A2 scenario (up to 3.9 Pg C yr^{1} in 2100) to a decrease in the B1 scenario (down to 0.8 Pg C yr^{1}). The global NPP is projected to increase up to 73-77 Pg C yr^{1} in 2050 and 77-88 Pg C yr^{1} in 2100. With regard to the net biosphere uptake, a robust finding from different baseline scenarios (and in line with other studies) is the projected increase up to the middle of the 21st century, followed by a stabilization or decrease.

The amplitude of this trend varies, however, among the different scenarios and experiments considered in this thesis. For example, keeping land use constant would lead to a higher natural response (i.e. a higher NPP increase) due to more natural biomes that are in C balance. The differences are less than expected on the basis of avoided land-cover changes only, because fewer land-use changes result in lower CO_2 concentration and thus a lower CO_2 fertilization. Overall, the terrestrial biosphere is projected to sequester 22- 46% of the total C fossil-fuel and land-use emissions during the 21st century.

Given the substantial role that land use and natural processes play in the terrestrial C cycle, as well as the geographical and temporal variation, I conclude that there is a need for an integrated approach to energy use, the natural ecosystems and land use, when simulating the behavior of the C cycle.

3. *What are key uncertainties in determining the response of the terrestrial C cycle to climate and land-use change?*

This thesis reflects the assessment of different uncertainties in ecosystem processes and land use and also a quantification of the effects of these uncertainties on the global and regional C cycle.

Experiments assuming different ecosystem responses to climate change and land use, and different baseline scenarios, show that these uncertainties have large consequences for the C cycle. It can, for example, not be ruled out that the current terrestrial C sink will turn this century into a C source. And uncertainties in future land-use change lead further to close to 100% difference in sequestration potentials of carbon plantations. When comparing the different elements of the global C cycle, uncertainties in ecosystem processes in response to climate change are shown to have larger consequences than uncertainties in future land use; these consequences are only slightly smaller than impacts of uncertainties in socio-economic drivers. Furthermore, the combined experiments show the overall uncertainty not be just the sum of the individual uncertainties. Interactions and non-linear behavior in the ecosystem response to climate change increase uncertainties.

What processes determine the large uncertainty in the ecosystem response to climate change and land use? I showed that the relevance of the processes depends on the scale considered. Globally, the most important source of uncertainty is the CO_2 fertilization effect. Regional climate, land use, CO_2 fertilization and soil respiration are most important in tropical regions. The C cycle in high latitudes has been mainly determined by CO_2 fertilization, temperature feedbacks, and the migration ability of species in response to climate change.

Unfortunately, the future strength of the CO_2 fertilization effect is still unknown, especially in natural vegetation. Different experiments and models use different assumptions and how to robustly scale the CO_2 fertilization effect to continental scales is still controversial. Developing robust parameterizations for this process should therefore be a key issue in climate change research.

Overall, I have shown that the response of the C cycle to climate and land-use change depends highly on the selected processes and their underlying parameterization. Some processes are more important than others –depending on the scale – and have multiple interactions. But all processes contribute substantially to the apparent uncertainty in the C cycle. This uncertainty should be considered in climate change mitigation studies, because it contributes to the build-up of CO_2 in the atmosphere. Furthermore, the non-linear responses obtained, along with their geographical and temporal variation, highlight the importance of considering the ecosystem responses to various pressures simultaneously.

4. *What is the potential role of the terrestrial biosphere in stabilizing the CO_2 concentration in the atmosphere?*

*In order t*o limit future climate change and its impacts, the U*nited Nations Framework Convention on Climate Change (UNFCCC) aims* to “stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system”. In addition to emission reductions from energy use, the Kyoto Protocol under the UNFCCC has recognized the importance of the terrestrial biosphere to achieve this objective. It provides explicit opportunities for developed countries to achieve some of their reduction commitments by planting new forests (so-called C plantations) or by managing existing forests or agricultural land in a different manner. This are the so-called Land Use and Land-Use Change and Forestry activities (LULUCF).

This thesis discusses the potential of all LULUCF options in a general policy context, as well as the economic and political implications. Specifically, I presented and applied a new methodology here to assess different global and regional sequestration potentials in C plantations, along with their effectiveness in stabilizing the CO_2 concentration in the atmosphere. The methodology – as implemented in the IMAGE 2 model – considers various limitations and concerns, as formulated in the Kyoto Protocol. This has not yet been achieved in other climate change mitigation studies.

Application of the innovative methodology for two different baseline scenarios up to 2100 indicates that uncertainties in future land-use change may lead to a near 100% difference in estimates of carbon sequestration potentials. Moreover, social barriers that prevent carbon plantations in natural vegetation areas may decrease the carbon sequestration potential by 75-80%. Nevertheless, taking the most conservative set of assumptions into consideration with respect to the land availability for food/feed production and the biodiversity concerns, carbon plantations could compensate for 5-7% of the energy and industry emissions up to 2100. The sequestration potential up to 2020 (incl. the first commitment period) is limited, given the short-term increased need for agricultural land in many regions and the long period needed to compensate for emissions during the establishment of new plantations. The largest potential develops beyond 2050 when more land becomes available and when established plantations start to sequester considerable amounts of carbon per unit area. Geographically, the C sequestration potential is highest in the tropics, although most of the agricultural expansion is also expected in these regions. The potential in high latitudes is limited and can even be unfavorable because of biogeophysical feedbacks. Plantations in these areas should only be established if the objective to sequester carbon is combined with other objectives like land protection or water management.

Based on a literature assessment, in general, and the IMAGE-2 application, in particular, I conclude that carbon plantations can play a large role in mitigating the build-up of atmospheric CO_2. The size of the role depends on the rules and accounting methods used and the timeframe considered. Furthermore, a number of ancillary benefits for local communities and the environment exist. Carbon plantations are, however, only effective in the long term. Furthermore, carbon plantations are not the ultimate solution to a stabilization of the CO_2 concentration. They must be part of a broader package of options with energy-emission reduction measures.

Although the only slight attention in climate change policy, the general behavior of the terrestrial biosphere is also important in defining policy measures required to stabilize greenhouse gas concentrations. The current terrestrial sink slows down the increase in atmospheric $CO_{2.}$ A robust finding among experiments presented here, but also in other studies, is a decrease in this sink after 2050. Such a decrease would imply more stringent emission reductions to achieve the UNFCCC objective of stabilizing GHG concentrations in the atmosphere.

5. *What is the applicability of intermediate-complexity models to simulate the past, current and future C cycle, especially in the context of climate-change policy development?*

The terrestrial C cycle is determined by numerous interacting processes that change over time and space. The processes include land use, and biogeochemical, biophysical, and ecological processes. Due to the complexity of the C cycle in the "real" world, processes are simplified in any terrestrial C cycle model. The problem in modeling the C cycle is to find an "optimal" extent of simplification. This is especially dependent on the objective of a model. IMAGE 2, as an example of Integrated Assessment (IA) models, is developed for primarily policy support. Particularly for these IA models, it is a major challenge to bridge the gap between policy needs (e.g. multiple-scenario analysis) and scientific rigor. This can only be achieved by a more reduced form of representation of various processes. Furthermore, detailed "information" – a particular system (such as individual species), a state variable (like biomass) or a process (like photosynthesis) – must be translated into general policy-relevant indicators and conclusions. In this thesis I present different concepts on how such information could be communicated. Reviewing the literature shows that the most suitable concept depends on the scales that have to be bridged, and on the type of information that needs to be scaled. Summation, for example, is difficult to apply for a large difference in scales (because of limited generalization and simplification). Here, aggregation is more useful, because the heterogeneity decreases, but then with the preservation of relevant interactions.

The backbone of this thesis is the terrestrial C-cycle model of IMAGE 2, which is an example of a model of intermediate complexity. Compared to other studies, the C cycle is assessed in IMAGE 2 in an integrated manner, simultaneously considering socio-economic drivers and natural processes, along with their interactions and feedbacks. The algorithms of the IMAGE-2 C-cycle model are derived from yield, gap, biogeographical and, especially, biogeochemical models.

The IMAGE-2 C-cycle model is positioned in this thesis in a broader context by comparing its results with observed trends, and different algorithms and results with other C-cycle models. These other models differ with respect to the objectives (e.g. science or policy support), scales (local to global), complexity, and comprehensiveness (ranging from highly aggregated models to complex process-based ones). Compared to simpler C-cycle models, IMAGE 2 is more process-based (including numerous interactions and feedbacks) and geographically explicit. The latter is important because the processes that determine the C cycle vary in space. Compared to more complex C-cycle models like DGVMs, various simplifications have been implemented in IMAGE 2 with respect to processes and scales. Ecosystem growth, for example, is implemented by using an average NPP value (for each biome) that is adjusted for climatic and local conditions. Furthermore, processes that determine the short-term C cycle (e.g. disturbances) and biogeophysical characteristics (e.g. surface roughness) are not included in the model.

The C pools and fluxes presented in simulations with IMAGE 2 are consistent with observations and findings of more detailed models on time scales ranging from decades to centuries. Applying the IMAGE-2 model for the past three centuries, for example, has yielded a well-reproduced atmospheric CO_2 concentration profile. The present-day NPP is about 60 Pg C yr^{1}, fitting well into the range of 58-62 Pg C yr^{1} cited in the literature. In projecting the future C cycle, IMAGE 2 estimates an NEP increase in the 1st half of the 21st century, followed by a decline. Qualitatively, this trend is in line with many other models. Quantitatively, some of the projected C fluxes are at the high end of existing ranges, probably due to a CO_2 fertilization effect that is too strong and an underestimation of changes in soil decomposition. Some of these assumptions should be adjusted in new IMAGE 2 versions to reflect the most recent insights, as was undertaken for IMAGE, version 2.4 (MNP, 2006, chapter 5).

On the basis of the comparison with the observations and with other model structures and results, I conclude that the IMAGE-2 C-cycle model has certain limitations with respect to simulating fine-scale (e.g. small-country or even grid) or very dynamic (e.g. seasonal or inter-annual) information. Furthermore, because of intermediate complexity and the limited characterization of biophysical processes, the IMAGE-2 C cycle model seems less suited to be coupled to complex climate models, something planned on the longer term. The IMAGE 2 C-cycle model is, however, an appropriate model for simulating the global and continental dynamics of the terrestrial C cycle on decadal to century time scales. Furthermore, due to its simplicity, simulating multiple scenarios is possible and assumptions can easily be changed or dropped. Using alternative assumptions enables a systematic evaluation of the robustness of the findings. Finally, due to the integration in a larger modeling framework, the effect of other processes relevant to the terrestrial C cycle (e.g. land use and socioeconomic developments) can be compared with uncertainties in the terrestrial C cycle. The integration also provides the possibility of quantifying policy-relevant indicators like atmospheric CO_2 concentration and global average temperature.

Overall conclusions

- The dynamics in the terrestrial biosphere play a critical role in determining the C cycle, the atmospheric CO_2 concentrations and thus the global climate on time scales ranging from months/seasons to centuries.
- Both natural processes and land use (changes) determine the C dynamics in the terrestrial biosphere. The importance of the underlying processes varies over time and geographical space. This creates a need for an integrated and geographically explicit approach for accurately determining the behavior of the future C cycle as a consequence of changes in energy use, land use, and environmental conditions.
- The IMAGE-2 C-cycle model is an appropriate model for simulating the global and continental terrestrial C cycle on time scales of decades to centuries.
- The terrestrial biosphere can play an important role in “stabilizing the greenhouse gas concentration in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system”. This important role has received insufficient attention in mitigation studies. However, given the importance of the energy sector, solely focusing in climate policies on slowing down deforestation or enhancing afforestation will not be sufficient for mitigating climate change.
- Different uncertainties in the biosphere have large consequences for the future C cycle. This can have considerable consequences for policy measures needed to achieve greenhouse gas stabilization. Reducing some of these uncertainties by developing robust parameterizations for processes like CO_2 fertilization should be a key issue in climate change research.

Samenvatting

Context

Het klimaat op aarde verandert. De gemiddelde temperatuurstijging in de 20e eeuw, bijvoorbeeld, was wereldwijd ca. 0.8°C en in Nederland ca. 1.0°C. Deze veranderingen zullen de komende eeuw zeer waarschijnlijk doorgaan. Voor het projecteren van het toekomstige klimaat in de 21ste eeuw is het noodzakelijk een schatting te maken van de toekomstige uitstoot van broeikasgassen, zoals kooldioxide (CO_2). Dit beeld is uiteraard onzeker. Men werkt daarom met scenario's, die verschillende plausibele ontwikkelingen in de toekomst beschrijven. Door het Intergovernmental Panel on Climate Change (IPCC) is in 2000 een 6-tal scenario's beschreven op basis van verschillende mondiale demografische, sociaal-economische en technologische ontwikkelingen. Al deze scenario's bevatten geen additioneel klimaatbeleid ten opzichte van het basisjaar en geven een uitgangspunt waarmee de effectiviteit van beleid kan worden vergeleken. Deze scenario's leiden tot verschillende uitstootniveaus van broeikasgassen. Aan hand van deze niveaus kan vervolgens de broeikasgasconcentraties in de atmosfeer en de grootte van de bijbehorende klimaatverandering berekent worden.

Ondanks de grote spreiding in de uitstoot van broeikasgassen, nemen in alle scenario's de concentraties van broeikasgassen in atmosfeer toe. Als gevolg daarvan stijgt de mondiaal gemiddelde temperatuur deze eeuw met 1.8 tot 4.0°C ten opzichte van het gemiddelde van 1980-2000. De spreiding in temperatuurstijging hangt samen met de onzekerheid over de schattingen van de toekomstige broeikasgasuitstoot en met een onvolledig begrip van het klimaatsysteem. Door de verdere opwarming kan het mondiaal gemiddeld meer en heviger gaan regenen en kunnen ook extreme weersomstandigheden vaker voorkomen. De verwachte veranderingen in neerslag hebben echter een sterk regionaal karakter. De toename zal vooral plaatsvinden in gebieden met een wateroverschot, terwijl de aride gebieden juist nog droger zullen worden. Voor Europa zal de kans op verdroging en extreme hitte toenemen (ook voor Nederland, maar vooral in Zuid-Europa).

Deze al waargenomen veranderingen in het klimaat hebben al tot verschillende zichtbare effecten geleid in natuur en maatschappij. De verwachting is dat de effecten sterk zullen toenemen in de komende decennia. Hierbij moet worden opgemerkt dat de effecten niet altijd negatief hoeven te zijn. Delen van de landbouwsector zouden bijvoorbeeld in sommige delen van Europa kunnen profiteren van een eerste, nog beperkte temperatuurstijging.

Het is zeer aannemelijk dat de geobserveerde klimaatveranderingen vooral veroorzaakt worden door de stijging van broeikasgassen in de atmosfeer, al spelen natuurlijke factoren (zoals vulkaanuitstoot en zonneactiviteit) en andere menselijke fatoren (b.v. verminderd aerosolconcentratie in de laatste decennia) ook een rol.

Om toekomstige klimaatverandering en de gevolgen daarvan te beperken is dan ook een substantieel verminderde uitstoot van CO_2 en andere broeikasgassen noodzakelijk, zodat hun atmosferische concentraties gestabiliseerd worden. Maar wat is ‘substantieel’? Het vaststellen hiervan vereist een beter begrip van de mondiale koolstofkringloop (in het Engels ‘C cycle’ genoemd), waar grote hoeveelheden koolstof (C) uitgewisseld worden tussen de verschillende compartimenten. Deze compartimenten zijn de atmosfeer, de terrestrische biosfeer (=het land met al haar ecosystemen en menselijke activiteiten), en de oceanen. De hoeveelheden C in en C-stromen tussen de verschillende compartimenten in deze kringloop bepalen de atmosferische concentratie en dus het klimaat. Zo nemen op dit moment de biosfeer en de oceanen ongeveer 55% van de menselijke CO_2 uitstoot op en vertragen daarmee de toename in atmosferische CO_2 concentratie. Maar het is vooralsnog onzeker hoe groot de opname door de biosfeer en oceanen in de toekomst zal zijn. Als deze (sterk) zal afnemen, wat mogelijk is, zijn grotere uitstootreducties noodzakelijk om de CO_2 concentratie te stabiliseren.

De terrestrische biosfeer is hierbij een belangrijke factor. Deze beïnvloedt de C-kringloop op 3 verschillende manieren:

- veranderingen in het historisch en huidige landgebruik, zoals ontginning en ontbossing, hebben substantieel bijgedragen aan de stijging in atmosferisch CO_2 concentratie.
- De resterende natuurlijke ecosystemen in de biosfeer nemen C op en vertragen de stijging van atmosferische CO_2 concentraties. Deze opname wordt echter beïnvloedt door het klimaat, vegetatietypen en landgebruik, en zal dus in de toekomst veranderen.
- Binnen het huidige klimaatbeleid is het geaccepteerd dat een veranderd beheer van bestaande bossen en aanplant van nieuwe bossen mogen worden meegenomen in het afremmen of zelfs stoppen van de stijging van CO_2 in de atmosfeer. Dit leidt ook tot een veranderend landgebruik.

In de biosfeer spelen vele fysische, chemische en ecologische processen een rol, die van elkaar afhangen en sterk reageren op veranderingen in het milieu en menselijk gedrag. Deze complexe samenhang maakt het moeilijk te voorspellen hoe de C-kringloop zich zal gedragen in de toekomst. Een manier om daar enigszins greep op te krijgen is door het ontwikkelen en toepassen van simulatiemodellen. Simulatiemodellen in het algemeen hebben bewezen zeer bruikbaar te zijn om de consequenties te kwantificeren van veranderde veronderstellingen over de C-kringloop en van verschillende scenario’s voor toekomstige maatschappelijke ontwikkeling. Het koolstofdeel van het simulatiemodel IMAGE 2 (Integrated Model for Assessing the Global Environment) is de ruggengraat van dit proefschrift. In het verleden heb ik aan de ontwikkeling van dit model bijgedragen. Het IMAGE-2 model bevat verschillende maatschappelijke (b.v. energie- en landgebruik) en natuurlijke processen die onderling samenhangen. Ontbossing in de wereld is bijvoorbeeld expliciet meegenomen als ook een stijgende houtvraag en het aanplanten van nieuwe bossen.

De doelstelling van dit proefschrift is het analyseren van *de reactie van de biosfeer op veranderende milieucondities en landgebruik en de consequenties hiervan op de C-kringloop in verschillende delen van de wereld.* Deze doelstelling is verder uitgewerkt in vijf onderzoekvragen, die hieronder worden beschreven en bediscussieerd. Deze vragen worden beantwoord door het IMAGE-2 model toe te passen voor de afgelopen drie eeuwen en voor verschillende toekomst scenario's voor deze eeuw. Verder wordt de structuur en de parameterisatie van het C-model van IMAGE 2 beschreven en worden de belangrijkste factoren, die de onzekerheid in de uitkomsten van het model bepalen, geanalyseerd. Tenslotte wordt het C-model van IMAGE 2 in een bredere context geplaatst door de resultaten van de historische analyse te vergelijken met waarnemingen en de scenarioresultaten te vergelijken met die van andere C-modellen. Deze andere modellen verschillen in complexiteit, variërend van hele eenvoudige tot zeer gedetailleerde modellen.

Onderzoeksvragen en discussies.

1. *Wat zijn de belangrijkste processen die de rol van het land in de C-kringloop bepalen?*

Ik laat in dit proefschrift zien dat de biosfeer een cruciale rol speelt in de C-kringloop op tijdschalen van maanden tot eeuwen. De biosfeer bevat grote hoeveelheden C en wisselt die relatief snel uit met de atmosfeer. Ondanks dat de diepe oceanen veel meer C bevatten, is hun rol in de C-kringloop vooral belangrijk op een tijdschaal van decennia tot millennia. Dit omdat het koolstof daar slechts zeer langzaam wordt uitgewisseld. Er zijn vele natuurlijke en antropogene (=door de mens bepaalde) processen die de rol van de biosfeer in de C-kringloop bepalen. Landgebruik is een zeer belangrijk antropogene proces, naast het gebruik van fossiele brandstoffen en cementproductie. Belangrijke natuurlijke processen zijn netto productie door fotosynthese (NPP), bodemrespiratie en verstoringen (b.v. bosbranden). Al deze processen beïnvloeden elkaar en veranderen als gevolg van milieuveranderingen. Verder hangt het belang van de verschillende processen ook af van ruimtelijke en temporele schaal waarop de analyse zich baseert. Een eenduidig resultaat van vele studies, inclusief dit proefschrift, is dat mondiaal gezien CO_2 fertilisatie (d.w.z. de reactie van fotosynthese op een stijging in atmosferisch CO_2 concentratie) zeer belangrijk is voor het berekenen van toekomstige concentraties. Op regionale schaal zijn er echter duidelijke verschillen. In de tropen zijn zowel CO_2 fertilisatie en bodemrespiratie belangrijk, in boreale streken is het vooral de fotosynthese-reactie op stijgende temperaturen. De uitbreiding van landbouw is momenteel het meest belangrijke antropogene landgerelateerde proces dat de C-dynamiek bepaalt in tropische regio's, terwijl in gematigde streken de bosbouw (houtoogst) domineert. Het analyseren van het relatieve belang van al deze processen is mogelijk geworden door een sterk verbeterd begrip ervan, dankzij laboratorium- en veldexperimenten, satellietwaarnemingen en het ontwikkelen van nieuwe modellen. Dit betere begrip heeft ondermeer geleid tot een bijstelling van de schatting van de mondiale NPP. Deze is in de loop van de tijd nauwkeuriger geworden van 45-68 $Pg.jaar^{-1}$ ($Pg = 10^{15}g$) tot 55-63 Pg $C.jaar^{-1}$ (en dit proefschrift 58-61 Pg $C.jaar^{-1}$). Verder constateren veel studies momenteel een stijging van de natuurlijke C-opname in de biosfeer in de komende decennia, maar een daling daarna. Toch blijven er substantiële regionale verschillen tussen de studies. Deze verschillen worden veroorzaakt door verschillen in gebruikte meetmethoden, definities en gebruik van verschillende periodes (bijv. het gemiddelde van de jaren 80 is anders dan het gemiddelde van de jaren 90).

2. *Wat zijn de consequenties van historische en toekomstige veranderingen in landgebruik en milieucondities op de regionale en mondiale C-kringloop?*

Ik presenteer in dit proefschrift nieuwe schattingen van de historische, huidige en toekomstige C-stromen die het gevolg zijn van veranderingen in landgebruik en natuurlijke milieucondities. De historische schattingen komen uit een studie waarin het IMAGE-2 model (versie 2.4) gekoppeld is aan de HYDE database van historisch landgebruik. De toekomstige schattingen komen uit een analyse waarin de meest onzekere parameters in IMAGE-2 (versie 2.3) bepaald zijn. Door IMAGE 2 te gebruiken is in beide studies gekozen voor een sterke integratie van de verschillende C-stromen. Met andere woorden, de stromen van en naar natuurlijke ecosystemen en door landgebruik (land- en bosbouw) zijn geïntegreerd met C-stromen die worden bepaald door de energiesector en door processen in de oceanen.

Gebaseerd op deze studie concludeer ik dat historische landgebruikveranderingen zeer belangrijk zijn geweest voor veranderingen in de C-stromen op het land, zowel mondiaal als regionaal. Veranderingen in landgebruik en natuurlijke processen hebben tussen 1700 en 2000 geleid tot een uitstoot van ongeveer 35 Pg C vanuit de biosfeer naar de atmosfeer. Zonder de veranderingen in landgebruik zou er een extra opname van ongeveer 142 Pg C zijn geweest. Dit verschil van 177 Pg is meer dan de helft van de C uitstoot van 308 Pg C door het gebruik van fossiele brandstof in dezelfde periode. Tot 1900 was de uitstoot door landgebruikveranderingen zelfs groter dan die van fossiele brandstoffen. In de afgelopen decennia is de rol van landgebruik verminderd, vooral doordat de C-opname in natuurlijke ecosystemen is gestegen (door bijv. klimaatverandering, CO_2 fertilisatie en stikstofbemesting). Volgens mijn berekeningen zou bijvoorbeeld de mondiale NEP (=netto C-opname in de biosfeer) gestegen zijn van bijna niets (=opname is gelijk aan uitstoot) in de periode 1700-1900 tot 2.1 Pg C.jaar^{-1} in de periode 1990-2000.

Het historische belang van landgebruik en natuurlijke processen varieert ook in de tijd en plaats. In Europa en de Verenigde Staten was landgebruik dominant tot het eind van de 19de/begin 20ste eeuw, resulterend in substantiële C-uitstoot. Rond 1950 veranderde dit beeld, toen agrarisch land uit productie werd genomen en er weer bebost werd, terwijl C-uitstoot door het gebruik van fossiele brandstoffen sterk is toegenomen. In meeste tropische regio's veranderde er op koolstofgebied relatief weinig tot 1950. De ecosystemen waren min of meer in evenwicht. De sterke ontbossing sinds 1950 voor de uitbreiding van landbouw heeft echter geleid tot een grote C-uitstoot en lagere natuurlijke opname. Dit maakt vele tropische regio's tot een C-bron. Het beperken van toekomstige landgebruikverandering moet dan ook gezien worden als een effectieve maatregel om de verdere stijging van de atmosferische concentratie te beheersen. Hierbij dient wel opgemerkt te worden, dat overal ter wereld de uitstoot door energiegebruik toeneemt. Hierdoor zal klimaatbeleid dat enkel gericht is op het vermijden van verdere ontbossing of het stimuleren van nieuwe bosaanplant nooit voldoende zijn om het klimaatprobleem substantieel aan te pakken.

Landgebruik en natuurlijke processen zijn ook van belang in de toekomstige C-kringloop. Hierbij zal het belang van de natuurlijk factoren en processen toenemen (door bijv. ander klimaat, hogere CO_2 concentratie), waardoor de bijdrage van landgebruik relatief gezien zal afnemen. Absoluut gezien echter, laten alle scenario's tot 2050 een toename zien van de uitstoot door landgebruik. Tussen 2050 en 2100 verschilt de trend tussen de scenario's van een verdere stijging tot 3.9 Pg C jaar^{1} in 2100 in het A2 scenario tot een daling tot 0.8 Pg C jaar^{-1} in het B1 scenario. De natuurlijke mondiale C-opname door planten (=NPP) stijgt in de scenario's van nu ongeveer 60 Pg C jaar^{-1} tot 73-77 Pg C jaar^{-1} in 2050 en 77-88 Pg C jaar^{-1} in 2100. Alle scenario's laten een stijging zien tot het midden van deze eeuw van NEP, gevolgd door een stabilisatie of een afname. Het kan zelfs niet worden uitgesloten dat het land omslaat van een C-put in een C-bron. Deze robuuste conclusie is in lijn met die van andere studies. Dit betekent dat de benodigde maatregelen om de atmosferische concentratie van broeikasgassen te stabiliseren versterkt moeten worden. De amplitude van deze trends verschilt echter tussen de scenario's en experimenten. In totaal bereken ik dat het land 22 - 46% van de C kan opnemen die wordt uitgestoten als gevolg van het gebruik van fossiele brandstof en veranderingen in landgebruik gedurende de 21ste eeuw.

Gegeven de belangrijke rol die landgebruik en natuurlijke processen hebben in de C-kringloop en vanwege de temporele en geografische variatie van deze rol, concludeer ik dat de C-kringloop alleen goed gesimuleerd kan worden als energiegebruik, natuurlijke processen en landgebruik op een geïntegreerde wijze worden geëvalueerd.

3 Wat zijn de belangrijkste onzekerheden die de respons van de C-kringloop op veranderingen in landgebruik en milieucondities bepalen?

In dit proefschrift worden verscheidene onzekerheden in natuurlijke ecosysteemprocessen en landgebruik beschreven, en worden de effecten van deze onzekerheden op de C-kringloop gekwantificeerd. De verschillende modelexperimenten laten zien dat het effect van onzekerheden op de C-kringloop groot is. Onzekerheden over toekomstig landgebruik leiden, bijvoorbeeld, tot een bijna 100% verschil in de potentiële C-opname in bosplantages. De consequenties ten gevolge van onzekerheden in natuurlijke ecosysteemprocessen blijken echter netto groter te zijn dan die ten gevolge van onzekerheden in toekomstig landgebruik. Verder blijken de consequenties van alle onzekerheden samen niet gelijk te zijn aan de som van de individuele onzekerheden. Niet-lineaire veranderingen van en interacties tussen de ecosysteemprocessen versterken de gezamenlijke onzekerheid. Ik laat in dit proefschrift zien dat de grote onzekerheid in de ecosysteemrespons op klimaat- en landgebruikverandering afhangt van de ruimtelijke schaal. Mondiaal gezien is de onzekerheid van het CO_2 fertilisatie-effect het grootst. In tropische regio's zijn onzekerheden in landgebruik, regionale klimaatverandering, CO_2 fertilisatie en bodemrespiratie het belangrijkst, terwijl de NPP respons op een veranderende temperatuur, CO_2 fertilisatie en de migratiemogelijkheden van soorten dominant zijn in boreale streken. Duidelijk is dat CO_2 fertilisatie een belangrijk proces is. De rol ervan in de toekomst blijft onzeker, vooral voor natuurlijke ecosystemen.

Experimenten en modellen, die in de literatuur beschreven zijn, gaan vaak uit van verschillende veronderstellingen en het is nog vooralsnog onduidelijk hoe resultaten en gevolgen in het veld of laboratorium geïnterpreteerd moeten worden voor grootschalige modelexperimenten. Een verhoogde aandacht van dit proces in klimaatonderzoek is dan ook zeer wenselijk, zodat een beter begrip en een robuustere modelparameterisatie ontwikkeld kan worden.

Samenvattend heb ik laten zien dat de C-kringloop sterk kan veranderen door veranderingen in CO_2 concentraties, klimaat en landgebruik. De consequenties van onzekerheden in de daarbij betrokken processen hangen af van de ruimtelijke schaal die men analyseert. Maar de totale onzekerheid blijft substantieel. Daarom is het aan te bevelen om deze onzekerheid mee te nemen in beleidstudies, die de noodzakelijke emissiereducties bepalen om atmosferische broeikasgasconcentraties te stabiliseren. Verder laat ik zien dat een precieze bepaling van de C-kringloop vereist dat interacties tussen betrokken processen worden verwerkt.

4. Wat is de mogelijke bijdrage van de terrestrische biosfeer in het bereiken van een stabilisatie van de CO_2 concentratie in de atmosfeer?

Om klimaatverandering en de effecten daarvan te beperken is er binnen het klimaatverdrag van de Verenigde Naties (VN) afgesproken om “de concentratie van broeikasgassen in de atmosfeer te stabiliseren op een zodanig niveau, dat een onverantwoorde menselijke invloed op het klimaatsysteem wordt voorkomen”. Het Kyoto-protocol, opgesteld in 1997 als aanvulling op het Klimaatverdrag, maakt het mogelijk om zo’n stabilisatie niet alleen te bereiken door de uitstoot van broeikasgassen zoals CO_2, te verminderen, maar ook door de aanplant van bossen (zogeheten C-plantages), vermindering van ontbossing of door een beter beheer van bestaande bossen of landbouwgebieden. Deze maatregelen leiden tot een grotere C-opname door de biosfeer en dus tot minder CO_2 in de atmosfeer.

Ik beschrijf in het kort de verschillende opties voor een verhoogde C-opslag in de biosfeer in een ecologische, politieke en socio-economische context.

Verder presenteer ik een nieuwe methode, die geschikt is om een verhoogd opnamepotentieel in C-plantages te bepalen en laat zien wat de mogelijkheden zijn onder verschillende veronderstellingen. Deze methode is vernieuwend omdat de verschillende beperkingen van en bedenkingen over C-plantages, zoals beschreven in het Kyoto-protocol, kunnen worden meegenomen.

Door deze nieuwe methode met behulp van IMAGE 2 toe te passen voor twee verschillende IPCC-scenario’s, laat ik zien dat de mogelijkheden voor C-plantages sterk uiteenlopen gedurende deze eeuw. De onzekerheden van toekomstig landgebruik leiden dan ook tot bijna 100% verschil in C-opname in dergelijke plantages voor verschillende scenario’s. Als daarbij sociale vraagstukken zoals natuurbescherming en voedselzekerheid worden meegenomen wordt de opnamecapaciteit met 75-80% gereduceerd. Maar zelfs met dergelijke strikte beperkingen kunnen C-plantages 5-7% van de CO_2 opnemen dat naar verwachting door energiegebruik en industriële activiteit tot 2100 uitgestoten zal worden.

Het opnamepotentieel in de komende decennia is echter zeer beperkt, omdat veel land nodig zal zijn om aan de stijgende voedsel- en hout vraag te voldoen en omdat plantages in de eerste jaren na aanplant netto (=inclusief de bodem) weinig C opnemen. Doordat na 2050 meer land beschikbaar komt en omdat de CO_2 opname van bestaande plantages flink stijgt met de tijd kunnen C-plantages dan ook pas effectief bijdragen aan het verminderen van de atmosferische CO_2 stijging. Geografisch gezien ligt het grootste opnamepotentieel in tropische regio's, ook al is hier veel land nodig voor voedselproductie. Het potentieel op hogere breedtegraden zoals Scandinavië en Siberië is laag. Aanplant van C-plantages daar zou zelfs kunnen bijdragen aan een opwarming van de aarde vanwege biofysische terugkoppelingen die de stralingsbalans en warmtebalans beïnvloeden (niet meegenomen in deze studie). Daarom moeten C-plantages daar alleen aangeplant worden als andere doelen zoals waterbeheer en natuurbescherming ook een rol spelen.

Gebaseerd op deze analyse concludeer ik dat C-plantages effectief kunnen bijdragen aan het afremmen van de CO_2 stijging in de atmosfeer. De mate waarin dit kan hangt sterk af van de (sociale) veronderstellingen, de wijze van berekening en de tijdshorizon. Maar in ieder geval is het een zaak van lange adem. Verder zijn C-plantages niet de ultieme oplossing om de gewenste atmosferische stabilisatie van CO_2 te bereiken. Zij moeten deel uitmaken van een breder pakket aan maatregelen, waarvan vermindering van de CO_2 zeer belangrijk blijft.

Naast de C-opname in plantages –die veel aandacht hebben in het huidige klimaatbeleid– is ook het gedrag van de natuurlijke ecosystemen bepalend voor de benodigde emissiereductiemaatregelen voor de gewenste CO_2 stabilisatie. Op dit moment nemen natuurlijke ecosystemen veel C op. Maar een robuust resultaat van mijn verschillende analyses en ook van andere studies is dat deze opname na 2050 zal afnemen. Het is dan ook zaak om in het verdere klimaatbeleid rekening te houden met deze daling.

5. *In hoeverre zijn relatief eenvoudige simulatiemodellen geschikt om het gedrag van de historische en toekomstige C-kringloop te beschrijven, vooral in de context van klimaatbeleid?*

De C-kringloop wordt bepaald door veel processen die onderling samenhangen en die sterk variëren in tijd en geografische ruimte. Door de complexiteit van de C-kringloop zullen in ieder simulatiemodel, hoe ingewikkeld ook, vereenvoudigingen nodig zijn. De uitdaging is het bepalen van de juiste mate van vereenvoudiging. Dit hangt met name af van het doel van een model. Het IMAGE-2 model is een zogeheten Integrated Assessment (IA) model, die met name ontwikkeld worden om beleid te ondersteunen. De hiermee samenhangende behoeften (bijv. veel scenario's doorrekenen in relatief korte tijd) kunnen alleen bereikt worden door een relatief vergaande vorm van vereenvoudiging. Verder moeten modelresultaten (zoals soortenverschuiving of veranderingen in C-opslag) omgezet worden in beleidsrelevante indicatoren. In dit proefschrift beschrijf ik verschillende methoden hoe beleidsrelevante informatie uit modellen als IMAGE 2 gehaald kan worden. Gebaseerd op een literatuuranalyse concludeer ik dat de geschikheid van een methode vooral afhangt van de temporele en geografische schaal. Hierbij spelen zowel de afstand in schaal (=afstand tussen een specifiek proces en de uiteindelijke indicator) en het type informatie een rol. De methode van "opblazen" (waarbij het totaal op de grote schaal de som is van de elementen op de kleine schaal), bijvoorbeeld, is nauwelijks toepasbaar als de afstand groot is, omdat processen en eigenschappen nauwelijks vereenvoudigd worden. “Aggregatie” (waarbij informatie samengevoegd wordt gebaseerd op overeenkomstige eigenschappen) is in dat soort gevallen veel bruikbaarder omdat de heterogeniteit in processen en eigenschappen afneemt terwijl de relevante interacties behouden blijven.

De ruggengraat van dit proefschrift is het C-model van IMAGE 2. In tegenstelling tot de meeste andere modellen worden in dit model socio-economische, fysische en ecologische dimensies geïntegreerd en interacties en terugkoppelingen tussen processen worden expliciet gemaakt. De vergelijkingen en veronderstellingen van het model zijn afgeleid uit gewas-, successie-, biogeografische en vooral biogeochemische modellen.

De robuustheid van het IMAGE-2 C-model is geanalyseerd door de resultaten van de historische analyse te vergelijken met waarnemingen, en door modelveronderstellingen en scenarioresultaten te vergelijken met die van andere C-modellen. Deze andere modellen verschillen in doel (vooral meer wetenschappelijk en minder beleid), het schaalniveau (lokaal tot mondiaal), complexiteit (van eenvoudige tot zeer gedetailleerde modellen) en volledigheid (weinig of alle processen geparameteriseerd). Ten opzichte van de meer eenvoudige modellen bevat IMAGE 2 meer interacties en terugkoppelingen en is geografisch expliciet. Deze geografische component is belangrijk omdat, zoals aangetoond, veel relevante processen variëren in de geografische ruimte. In vergelijking tot meer complexe modellen zoals DGVMs (Dynamic Global Vegetation Models) zijn in IMAGE 2 veel processen vereenvoudigd en zijn schalen gereduceerd. De C opname in ecosystemen, bijvoorbeeld, wordt in IMAGE 2 gesimuleerd door gebruik te maken van een gemiddelde NPP waarde per ecosysteem, die aangepast wordt voor lokale klimaat- en milieucondities. Verder zijn processen die de korte-termijn dynamiek (b.v. bosbranden) en biofysische eigenschappen van de C-kringloop (bijv. ruwheid van het aardoppervlak) beschrijven niet meegenomen.

De resultaten van deze vergelijkingen laten zien dat de gesimuleerde C-opslag en fluxen goed overeen komen met waarnemingen en met de lange-termijn resultaten (van decennia tot eeuwen) van de meer complexere modellen. De historische analyse, bijvoorbeeld, laat een zeer goede overeenkomst zien met de waargenomen trend in de atmosferische CO_2 concentratie. Ook de huidige NPP van ongeveer 60 Pg C jaar^{-1} komt zeer goed overeen met literatuur (58-62 Pg C jaar^{-1}). Voor wat betreft de scenarioanalyse laat IMAGE 2 een toename in NEP zien gedurende de eerste helft van deze eeuw, gevolgd door een daling. Kwalitatief komt dit overeen met de resultaten van vele andere modellen, maar kwantitatief is de NEP relatief hoog ten opzichte van andere studies. Vermoedelijk komt dit door een (lichte) overschatting van het CO_2-fertilisatie-effect en een onderschatting van de verandering in bodemdecompositie (als gevolg van klimaatverandering). Dit inzicht heeft al geleid tot aanpassing in IMAGE versie 2.4, zoals dat voor hoofdstuk 5 gebruikt is.

Op basis van de genoemde vergelijkingen van het IMAGE-2 C-model met waarnemingen en andere modellen, concludeer ik dat het model zijn beperkingen heeft wat betreft het simuleren van zeer dynamische en fijnschalige processen.

Verder is het model vanwege verschillende vereenvoudigingen en afwezigheid van enkele biofysische parameters minder geschikt om gekoppeld te worden aan zeer gedetailleerde klimaatmodellen. Maar het model is zeker geschikt voor de simulatie van de mondiale en regionale C-kringloop voor de middellange (decennia) en lange (eeuwen) termijn. Verder is het goed mogelijk om door de eenvoud van IMAGE 2 op relatief korte termijn veel scenario's door te rekenen en de gevolgen van bepaalde veronderstellingen en toevoegen of weglaten van verschillende processen te evalueren. Dit soort systematische analyses verhoogd het vertrouwen in de bevindingen en geeft inzicht in de onzekerheden. Tenslotte is de integratie van het model een groot voordeel, omdat dit de mogelijkheid biedt om de C-kringloop van vele kanten (inclusief landgebruik en socio-economische ontwikkelingen) te bekijken. En die integratie maakt het mogelijk om beleidsrelevante indicatoren te implementeren en verder te ontwikkelen.

Algemene conclusies

- Veranderingen in de terrestrische biosfeer spelen een cruciale rol in het beschrijven van de C-kringloop, de atmosferische CO_2 concentratie en dus het klimaat op aarde, vooral op tijdschalen van een maand tot een eeuw.
- Zowel natuurlijke processen als (veranderingen in) landgebruik bepalen de C-kringloop in de biosfeer. De bijdrage van de achterliggende processen verschilt in tijd en ruimte. Daarom is een integrerende en geografisch expliciete aanpak noodzakelijk om veranderingen in de C-kringloop als gevolg van veranderingen in energiegebruik, landgebruik en omgevingsfactoren goed te kunnen bepalen.
- Het C-model van IMAGE 2 is een geschikt model om de mondiale en regionale C-kringloop op land te simuleren op middellange en lange termijn (decennia, eeuwen).
- De terrestrische biosfeer kan een belangrijke bijdrage leveren aan het stabiliseren van de broeikasgasconcentratie in de atmosfeer, waardoor klimaatverandering verminderd kan worden. Dit krijgt nog onvoldoende aandacht in het klimaatbeleid. Aan de andere kant, beleid dat zich alleen richt op deze processen in de biosfeer zoals het vermijden van ontbossing en het stimuleren van bosaanplant zal ook nooit voldoende zijn om klimaatverandering te vermijden, omdat de energiesector de meest belangrijke bijdrage zal blijven leveren.
- Onzekerheden met betrekking tot processen in de terrestrische biosfeer hebben grote gevolgen voor het kwantificeren van de toekomstige C-kringloop. Dit op zijn beurt heeft weer gevolgen voor het te voeren klimaatbeleid en de daarmee voortvloeiende uitstootvermindering van broeikasgassen. Daarom is een beter begrip van bepaalde processen, zoals CO_2 fertilisatie, en hun interacties, en het daarmee verkleinen van de onzekerheid, essentieel. Dit zou deze meer aandacht moeten krijgen in het klimaatonderzoek.

Acknowledgments

After more than 10 years, the die has finally been cast. My thesis is a fact. For me a relief – for you, possibly a surprise. The process has not been an easy one, with a lot of ups and downs, changing topics and so many other interesting things, both private and professional. But, at last, here it is!

Writing this thesis would not have been possible without the support and understanding of many colleagues, friends, family, and others, many of whom kept reminding me that writing a thesis was actually a worthwhile undertaking. For this, and for your contribution to the thesis, I wish to thank you all.

Firstly, I thank, in particular, my supervisors, Rik Leemans, Rob Swart, and Bas Eickhout.

Dear Rik, we have worked together for more than 15 years now. During that time I learned a lot from you about climate change, land use, and environmental modeling. Our challenging discussions on different issues have been included in a number of our joint papers. These discussions were not always easy, and this thesis must have been the toughest job, also for you. Thanks very much for the patience, and the hard, but constructive, comments on my early drafts. I hope we can continue our cooperation in the coming years.

Dear Rob, I still consider it one of my smartest moves to ask you to be second supervisor. Having my superior involved in this thesis helped me to set priorities for finalizing the work. And you had the special qualities to assist me with this. Content wise, your critical comments on the different model experiments and early text always came as a relief for me, even though you usually saw yourself as a non-expert in the field of C-cycle modeling. Further to this, I want to thank you very much for preparing this creative cover for my thesis. From the beginning we had the same ideas about what it should portray.

Dear Bas, I would like to thank you for your support in different places in this thesis. However, I must follow the rules and can do it only here. Your views on both possible and impossible experiments were crucial, and your comments on a number of texts helped me greatly in focusing and improving the writing. Without you, the work would likely still not be finished. Thank you!

Secondly, I thank Jan Goudriaan and Louise Fresco. You might be surprised at this mention, but our discussions in different places around the world stimulated me to start work on this thesis. You both have always been very inspiring. Despite switching from the main issue at that time, i.e. scales and scaling in ecological modeling, to my chosen theme, the former is still of personal interest to me (I may even write a book on this topic once). Nevertheless, I did appreciate your “grandfathering” back then.

Thirdly, I extend a word of thanks to my colleagues at the Netherlands Environmental Assessment Agency (MNP). I look to my colleagues at LED (European Air Quality and Sustainability) and KMD (Global Sustainability and Climate Change). I want to start with the IMAGE group of KMD, with whom I worked as an “outsider” (coming from LED), but you never let me feel that way. My special thanks goes to Bart for our joint work on carbon plantations. The endless discussions on BEFs, AGBs, NPPs, etc. will remain for a long time in my memory. Further, thanks to Bas, Elke and Kees, with whom I had various difficult discussions about IMAGE 2 and the historical C cycle. However, the discussions were always constructive and held in a congenial atmosphere. Thank you very much, Rineke, for the fantastic programs that enabled me to convert IMAGE 2 output into something that I could understand and use in my papers. Finally, Tom, Lex, Paul, Detlef, Roy, Bas, Morna, Michel, and the others of the IMAGE group: it was then, and is now, a pleasure to work with you. Furthermore, let me not forget my colleagues at LED, who have greatly supported me over the past years in finalizing this thesis. Hans, Jos, Bart, Peter, Frank, Chris, Rob and others, thank you very much!

I also want to thank other colleagues who took over some of my duties the last six months. In this context I refer especially to Michel Bakkenes and Rob Alkemade from MNP, Thomas Voigt and Benno Hain from ETC, and Andre Jol, Pavel Stastny, Jane Feehan, and Ricardo Fernandez from the EEA. Your involvement made it possible for me to work on this thesis without having to worry about my other responsibilities. It is even somewhat frightening to think that not too much has gone wrong. Thanks very much, and I look forward to working with you in the future.

I would also like to mention the MNP Management Team, whom I acknowledge for giving me the opportunity to work on this thesis, even during normal working hours on occasion. Specific thanks go to Bert Metz, Keimpe Wieringa, Rob Maas, and Klaas van Egmond. I am also indebted to Ruth de Wijs, English-language editor, for her language support. Due to the tight schedule at the end we were not sure about whether it would be possible for you to read all the draft chapters. But you did it, and at an amazing speed! Thanks very much.

I am not only indebted to colleagues at MNP, ETC, and the EEA, but also to colleagues and friends outside this circle, especially Joe Alcamo, Günther Fischer, and Mike Apps. Apart from working with you and gaining from your expertise, I very much enjoyed the informal “meetings”– the different (wine) parties, hikes in Kassel and around Vienna, and sailing tours in the waters near Vancouver. You frequently asked about my progress with the thesis, made interesting suggestions, and stimulated me to finish this “job”. Thanks very much to you and your families for the friendship. Here, I must also thank others in the C-cycle community, especially Wolfgang Cramer, Stephen Sitch, and Dennis Ojima. Our discussions on different aspects of the global C cycle helped me to broaden my knowledge, culminating in the incorporation of these aspects in my thesis.

A few special words also to my family and friends for the patience you have shown over the past years. I'm sorry that I couldn't attend many of the birthday parties or accept your invitations to play tennis or go for a run, or that I had to cancel attractive social events. I can now absolutely confirm the common perception that writing a thesis is only possible by sacrificing your social life. I hope, and expect, to be more available for invitations in the future. Last but not least, a very special word of thanks to Annette and the kids.

Dear Annette, you have always been my tower of strength. About 10 years ago you wrote in your thesis that you were hoping for more time together after it was all over. Well, let's get back to this point and really make that time now!

Lieve Karin & Wouter,

Het is ook jullie 'schuld' dat het zo lang geduurd heeft. Maar dat had ik er graag voor over. Papa's boekje is nu af en hij wordt nu doctor (geen dokter). Het zijn bij elkaar ongeveer 250 bladzijden geworden. Papa zal nu minder op zolder hoeven te zitten. Laten we nu bijvoorbeeld gauw met de trein gaan spelen, iets van lego bouwen of naar de speeltuin, dierentuin of het 'huisje in het bos' gaan. Het is aan jullie om te zien of wat papa heeft opgeschreven ook realiteit wordt in komende decennia.

Although I have thanked numerous people here, I'm sure I have forgotten somebody. Please forgive me. When we meet again I'll do my best to put this right.

Curriculum Vitae

Jelle van Minnen has been on the move internationally for a good part of his life.
He was born on 9 March 1964 in Luxembourg City, Luxembourg. After completing his primary school in Bonn, Germany and his secondary school education (VWO) in Breukelen, the Netherlands, he went on in 1982 to study forestry at the Wageningen University and Research Centre (WUR). Jelle graduated from the WUR in 1988 with the specialization in forest ecology and environmental science. During his studies he spent six months at the Norwegian Forestry Institute in As, Norway.

In 1989 Jelle accepted a position at the National Institute of Public Health and the Environment (RIVM) in Bilthoven, the Netherlands. During his first six years there he developed different simulation models on impacts of environmental change on the Netherlands and across the globe. Global effects were incorporated into his research in the early development of the IMAGE-2 C-cycle model. In 1995 he moved on to the International Institute of Applied Systems Analysis (IIASA) in Laxenburg, Austria for two years, where he worked on the causes and effects of historical changes in land use and land cover in northern Eurasia (China, Mongolia, and Russia). This period was followed by three years at the Center for Environmental Systems Research, University of Kassel, Germany. Here, Jelle's work focused on assessing the consequences of climate (variability) and land-use change on multiple receptor systems in Germany, Europe, and across the globe. He also developed tools to assess the combined effect of climate change and regional air pollution within Europe.
In 2000 Jelle returned to the RIVM's division of Environmental Assessment, which became the Netherlands Environmental Assessment Agency (MNP) in 2006. Here, Jelle's work on causes of climate change, impacts, and adaptation took place mainly within the European Topic Centre for Air and Climate Change. He also became involved in the further development of the IMAGE-2 model, which is documented in this thesis.

Jelle has now 18 years of experience on the development and application of Integrated Assessment (IA) models. Furthermore, he has set up environmental databases and Geographic Information Systems (GIS), and has participated in policy-supporting activities. These have focused on the impact assessment of climate change, air pollution, and land-use changes on different receptor systems in different areas across the world. Climate change adaptation has recently been added to Jelle's activities. Finally, scaling and aggregation problems of environmental/ ecological information have attracted his personal interest, triggered by the work on the local, national, European, and global levels.

Jelle has documented his research in over 20 papers in peer-reviewed journals. He has also contributed to several chapters of the Second, Third and Fourth Assessment reports of the Intergovernmental Panel on Climate Change (IPCC), and to numerous reports for the RIVM/MNP, European Environmental Agency, and the European Commission. In all of these activities Jelle has been able to count on an extensive network of contacts throughout the world.