Forest Management for Climate Change Mitigation

Modeling of Forestry Options, their Impact on the Regional Carbon Balance and Implications for a Future Climate Protocol

Inaugural-Dissertation zur
Erlangung der Doktorwürde
der Fakultät für Forst- und
Umweltwissenschaften der
Albert-Ludwigs-Universität
Freiburg i. Brsg.

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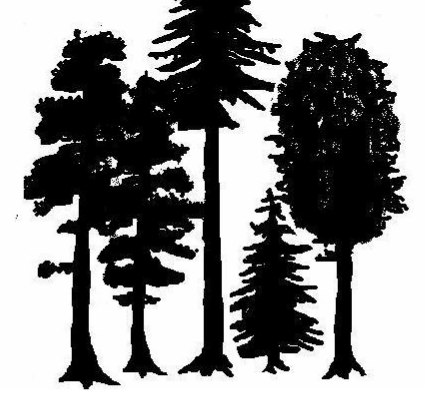
Freiburg im Breisgau
2007



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Datum der Disputation: 26. November 2007

für Kathi und Heinz

The noble simplicity in the works of nature only too often originates
in the noble shortsightedness of him who observes it.
(Georg Christoph Lichtenberg)

ACKNOWLEDGMENTS

First, I want to thank my supervisor Annette Freibauer, for her continuous support during my PhD. Annette was always there to listen and to give advice. She is responsible for involving me in the dissertation topic in the first place. Thanks to her support I was able to meet, interact and learn from many fellow researchers. I greatly appreciated the freedom that I had, as well as her confidence in me.

Prof. Dr. Ernst-Detlef Schulze is gratefully acknowledged for supporting this thesis and for allocating his precious time for me in fruitful meetings.

I am very grateful to Prof. Dr. Jürgen Bauhus for adopting me as a foreign student and being a referee of the thesis.

Besides my advisors, I would like to thank the colleagues of my thesis committee, Galina Churkina, Thomas Wutzler and Christian Wirth for their critical comments, support and enthusiasm of doing science.

I wish to thank Werner Kurz and the Carbon Accounting Team at PFC for two months on their magnificent island. Werner is specially thanked for precious comments on parts of the manuscript.

I am grateful to Michael Obersteiner for his epidemic optimism and for hosting me during the last months of my PhD as well as for comments to parts of the manuscript.

The following colleagues I would like to acknowledge for supporting this thesis with providing data. These are in particular Martina Mund, Mona Vetter, Angelika Thuille, Youmin Chen from MPI BGC, Till Pistorius (Uni Freiburg) and Ingolf Profft (TLWJF). Gert-Jan Nabuurs (EFI) for providing the EFISCEN database. Yvonne Scholz and Vincent Gitz taught me about energy and substitution. Susanne Sprauer and Simon Geissler helped with data processing and aggregation.

Anke Herold and Niklas Höhne as project partners, as well as Rosemarie Benndorf, introduced me to the world of climate policy, which gave me new perspectives to my work.

Funding over the course of three years was provided by the German Umweltbundesamt (UBA) through the project FKZ 203 41 148/02 „Senken in der 2. Verpflichtungsperiode". I was further supported by grants from the German National Member Organization at IIASA during three months in the Young Scientists Summer Program at IIASA. A two months stay at the Pacific Forestry Center was funded by a Doktorandenstipendium of the German Academic Exchange Service (DAAD). The Canadian Forestry Service kindly hosted me.

My time in Jena at MPI BGC included life beyond science thanks to Axel and Catharina, Annett, Fernando, Tiemo and many more.

I thank Anna Lena, Charlotte, Ilona and Wolfgang for being my family and their support and encouragement.

My wife Sirle, to whom my love keeps growing like a Douglas fir in the Cathedral Grove, for everything.

CONTENTS

LIST OF PUBLICATIONS

I Böttcher, H., A. Freibauer, M. Obersteiner and E.-D. Schulze, in press. Uncertainty analysis of climate change mitigation options in the forestry sector using a generic carbon budget model. Ecological Modelling. doi:10.1016/j.ecolmodel.2007.11.007.

II Freibauer, A., Böttcher, H., Scholz, Y., Gitz, V., Ciais, P., Mund, M., Wutzler, T., Schulze, E.-D., submitted. Setting priorities for land management to mitigate climate change. Submitted to Climatic Change

III Böttcher, H., Kurz, W. A., Freibauer, A., submitted. Accounting of forest carbon sinks and sources under a future climate protocol - factoring out past disturbance and management effects on age-class structure. Submitted to: Environmental Science and Policy.

STATEMENT ABOUT PUBLICATIONS AND OWN CONTRIBUTION TO THE PUBLICATIONS

Coauthors contributed to all three publications in different ways. To identify my own contribution to each of them I used an authorship index as proposed by Hunt (Hunt, 1991). Points from 0 to 25 indicate the contribution to four categories (see respective Tables below). To acknowledge the contribution of coauthors the expression “we” that occurs in the publications was kept in the thesis.

Publication I incorporates Chapter Two and Four of the thesis, the model description and the analysis of sensitivity and uncertainty. I developed the modeling approach and compiled the model FORMICA. I further carried out the entire analysis of sensitivity and uncertainty on my own. The coauthors gave feedback to the implementation of algorithms and commented on the manuscript.

	Intellectual input	Practical input: modeling	Practical input: data processing	Literary input	**Sum**
Hannes Böttcher	25	25	25	25	**100**
Annette Freibauer	10	10	0	5	**25**
Michael Obersteiner	10	5	0	5	**20**
E.-Detlef Schulze	0	0	0	5	**5**

Publication II is based on Chapter Three of the thesis. The study is a joint effort of a larger group of people. I carried out the entire quantitative analysis where the FORMICA model was involved (about 80% of the analysis). The calculation of the substitution efficiency was done by Yvonne Scholz. Results were discussed in group meetings. Annette Freibauer coordinated the study and is therefore the first author of the publication. Together with her I formulated discussion and conclusions.

	Intellectual input	Practical input: data capture	Practical input: data processing	Literary input	**Sum**
Annette Freibauer	25	15	10	25	**75**
Hannes Böttcher	20	15	20	20	**75**
Yvonne Scholz	10	15	10	5	**40**
Vincent Gitz	10	10	5	5	**30**
Philippe Ciais	10	5	0	5	**20**
Martina Mund	5	5	5	5	**20**
Thomas Wutzler	5	10	5	5	**20**
E.-Detlef Schulze	10	5	0	5	**20**

Publication III corresponds to Chapters Five and Six. The study was carried out in cooperation with Werner Kurz at the Pacific Forestry Centre, Canada. He helped me to focus the analysis and with suggestions to the modeling approach. Both coauthors provided help in formulating the problem description and conclusions and added their thoughts to it.

	Intellectual input	Practical input: data capture	Practical input: data processing	Literary input	**Sum**
Hannes Böttcher	20	20	25	20	**95**
Werner Kurz	20	15	10	15	**60**
Annette Freibauer	15	0	10	15	**40**

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LIST OF ABBREVIATIONS

ACS	Average Carbon Stocks
BaU	Business as Usual
C	Carbon
CBM-CFS	Carbon Budget Model of the Canadian Forestry Sector
CO_2	Carbon dioxide
COP	Conference of the Parties
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FORMICA	FORest Management Impact on CArbon dynamics
GHG	Greenhouse gas
GPP	Gross primary production
Gt	Gigatonne
ha	Hectare
IPCC	Intergovernmental Panel on Climate Change
LULUCF	Land-Use, Land-Use Change and Forestry
Mha	Million hectares
MRT	Main residence time
Mt	Megaton
N	Nitrogen
NAR	Net annual revenue
NBP	Net biome production
NEP	Net ecosystem production
NPP	Net primary production
NPV	Net present value
ppm	Parts per million
Ra	Autotrophic respiration
Rh	Heterotrophic respiration
stdev.	Standard deviation
t	Tonne
UNECE	United Nations Economic Commission for Europe
UNFCCC	United Nations Framework Convention on Climate Change

INTRODUCTION

Most of the observed increase in global average temperatures over the past half-century is very likely due to the observed increase in atmospheric greenhouse gas (GHG) concentrations (IPCC, 2007). Now that global warming is largely recognized as a serious threat to nature and society, the global community is searching for cost-effective means of slowing down the further increase in atmospheric concentrations of GHGs like CO_2 and others. It is often overseen, that approximately 40% of the emissions that occurred during the last 20 decades were caused by land-use change (DeFries et al., 1999). Changes in terrestrial carbon (C) stocks have significantly contributed to the increase of GHGs in the atmosphere (Houghton and Hackler, 2001). The overall C losses of the biosphere due to land-use and land-use change (LULUCF) are considered to amount up to 170 Gt C having caused atmospheric CO_2 concentration levels to rise by 40-70 ppm (House et al., 2002).

Despite their past and recent extended losses in area, the remaining global forests turn over approximately one-twelfth of the atmospheric stock of carbon dioxide through gross primary production (GPP) every year (Malhi et al., 2002). But less than 1% of the carbon that is turned over ends up in a long-term terrestrial carbon sink (see Box 1). The special role of forests in the global carbon cycle that differs significantly from other components is due to the properties of carbon pools in forest ecosystems. Comparably high carbon stocks were accumulated over centuries after the last glaciation, amounting currently to about 1640 Gt of carbon (Sabine et al., 2004). The slow build-up through photosynthesis funneled into forest growth is contrasted by the risk of a rapid release through disturbances such as fire and harvest (Körner, 2003). Forest ecosystems integrate over various carbon pools of different turnover rates. The average residence time of carbon in forest biomass in unmanaged tropical systems is ranging from 50 to 100 years (Vieira et al., 2005). In systems where harvest or natural disturbance releases carbon earlier, the average age of carbon is lower.

Box 1: The terrestrial carbon cycle

The strength of the forest sink or source is equivalent to the difference between assimilating and respiratory processes. CO_2 assimilation by plants takes place as long as the gross primary production (GPP) exceeds autotrophic respiration (Ra), i.e. respiratory losses related to plant growth and maintenance and can be expressed as net primary production (NPP=GPP-Ra). According to Steffen et al. (1998) about 50% of the initial uptake through GPP is used by plants for growth and maintenance (Figure 1).

Considerations on an ecosystem level have to include external respiratory losses (heterotrophic respiration, Rh), i.e. release of carbon due to decay of biomass into the atmosphere, resulting in the net ecosystem production (NEP=NPP-Rh). NPP and Rh are not independent from each other and driven by different parameters. Carbon losses related to ecosystem management, e.g. disturbances (D) and timber harvest (H), are accounted for in the net biome production (NBP=NEP-D-H). NBP is the critical parameter to consider for long-term carbon storage at the ecosystem level.

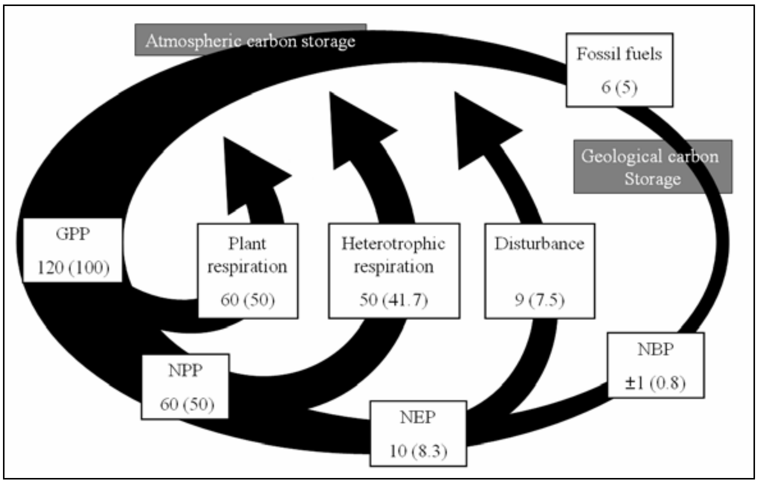

Figure 1: The terrestrial carbon cycle in Gt carbon per year. Values in parentheses show percent of GPP (after Bolin and Sukumar, 2000).

Currently, recovering forest ecosystems and forest expansion in the Northern Hemisphere form a sink of CO_2 from the atmosphere. According to the IPCC (2001) the global net uptake of terrestrial ecosystems from 1990 to 1998 was around 2.4 Gt of carbon per year (Bolin and Sukumar, 2000, Schimel et al., 2001). These estimates are highly uncertain. Uncertain is also the individual share of processes contributing to the sink. Various indirectly human-induced processes depending on the region of the world (anthropogenic nitrogen deposition in Europe, increasing global temperatures in Siberia, and maybe rising CO_2 in tropical regions) are considered to contribute (Schulze, 2006; Canadell et al., 2007a; Canadell et al., 2007b). Estimates of the fraction of direct human-induced impact on the forest sink due to management change vary widely but are quite high (40 – 98% management-induced, Houghton 2003). A further restoration of terrestrial ecosystem carbon stocks could hold a potential of 60-87 Gt carbon that could be conserved or sequestered only in forests by the year 2050 (Kauppi and Sedjo, 2001).

But mitigation services of forests can go beyond the ecosystem level. Additional to carbon stored in forest ecosystems, forests provide harvestable products that a) contain carbon themselves and b) compete with other materials and products (whose production is more or less carbon intense) on a global market, having implications for the cross-sectoral global carbon balance (Kauppi and Sedjo, 2001). Therefore, three strategies to curb the increase of CO_2 in the atmosphere are available and have to be distinguished: conservation (prevent emissions from existing forest carbon pools), sequestration (increase stocks in existing pools) and substitution (substitute energy-intensive products or products on fossil fuel basis with products from regrowing resources, including the generation of energy).

Box 2: Article 3.4 of the Kyoto Protocol

Additional activities to afforestation, reforestation and deforestation (treated in Article 3.3) are treated under this Article of the Kyoto Protocol. These include among cropland management, grazing land management and revegetation also forest management. Accounting for each of these activities is voluntary in the first commitment period. The decision on activities to be accounted has to be taken before the commitment period and remains fixed for its duration. All activities have to be occurred since 1 January 1990. The accounting under article 3.4 is based on a 'gross-net approach', meaning that emissions or removals from the elected activities are not accounted for in the base year (gross), but only in the commitment period (net). Thus, only the change during the commitment period is relevant for the accounting and not the change since the base year (Figure 2, Höhne, 2006).

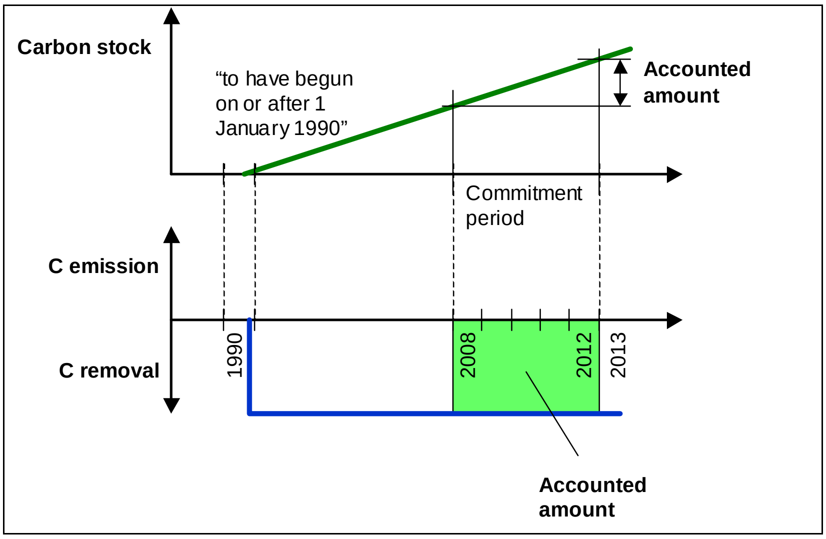

Figure 2: Accounting for afforestation, reforestation and deforestation as well as forest management under the Kyoto Protocol showing changes in carbon stocks (top) and, with different scale, carbon emissions (bottom, Höhne, 2006).

Under the Kyoto Protocol industrialized countries are committed to reduce their GHG emissions in the period of 2008 to 2012 by roughly 5% compared to emissions in 1990. The negotiating parties created an option for countries to elect activities in land-use, land-use change and forestry (LULUCF) to be accounted for (see Box 2). Article 3, paragraph 4, of the Kyoto Protocol allows choosing any of forest management, cropland management, grazing land management and revegetation activities for meeting a country's commitment. The maximum contribution of the forest management sink to the commitment was negotiated and is limited to country-specific caps. This was a way to take into account the different character of this sector compared to emissions from fossil fuels (Höhne, 2006). This special character is expressed through a) a two-way direction that C can take (LULUCF can be sink or source), resulting in b) non-permanence of a large part of the sink potential and c) dependency of sink or source on past practice and disturbance.

Twenty[1] out of the 37 countries that ratified the Protocol elected forest management under Article 3.4, among them countries with extensive forest areas like Russian Federation, Norway, Finland, Sweden, Germany, Slovenia and Switzerland. Most of them probably expect their managed forest areas to act as a sink during the first commitment period of 2008 to 2012 and help them fulfill commitments of emission reduction. Some parties with extensive forests did not elect forest management due to risks of carbon release through forest fires (e.g. Canada).

However, parties and the scientific community lack detailed knowledge about the potential of forest management to mitigate climate change, at national to global, and decadal to centennial scales, and about associated uncertainties and constraints. This thesis explores the impact of past and present management on forest C stocks and stock changes and quantifies the potential for climate change mitigation. In detail, the following research questions are addressed:

- **What is the impact of different forest management options on C stocks and fluxes in forest ecosystems, on C stored in harvested wood products and forest product derived fossil fuel C substitution? What are the mechanisms?**

Chapter One introduces this issue and gives an overview of the general potential of forest management as a mitigation measure by analyzing its impact on forest carbon stocks in various pools and on various scales. *Chapter Two* presents basic algorithms and parameters

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[1] State on November 8, 2007

of the forestry model FORMICA that has been developed as a part of this thesis to answer the scientific questions.

- **Which land-use options are most effective for climate change mitigation and at the same time economically optimal?**

How forest and cropland management offer significant potential for cost effective climate change mitigation in particular is demonstrated in *Chapter Three*. Based on data of the German federal state of Thuringia, the model framework is used to evaluate climate benefits and land-owner revenue for competing demands for products, energy and climate change mitigation.

- **Which are important parameters and input data for a C budget model of the forestry sector? What are the associated uncertainties? Can the potential of different options of management change be quantified against these uncertainties?**

An analysis of model sensitivity to changes in key parameters and an evaluation of parameter and model uncertainty is the focus of *Chapter Four*. For conditions in Thuringia the impact of management change scenarios on the C balance of a landscape is contrasted with the underlying model uncertainty.

- **What are drivers of carbon sinks and sources of managed forests on a regional scale? How can they be identified and accounted for in a climate effective accounting scheme?**

Chapter Five identifies major processes and takes a look at effects of past practices and natural disturbances on regional carbon stocks in managed forests. It also examines how they can be differentiated computationally from today's observable carbon dynamics. Presented approaches are evaluated in terms of applicability, verifiability, and ability of providing incentives for climate-friendly forestry.

- **What is the biological/technical potential of forest management activities in Europe? What are implications of proposed accounting schemes for single countries?**

Chapter Six quantifies the impact of past practices and future forest management scenarios in European countries and shows implications of the various ways of accounting for countries identifying 'winners' and 'losers' of each approach.

ONE

FOREST MANAGEMENT FOR CLIMATE CHANGE MITIGATION: POTENTIALS AND FEEDBACKS

ONE.1 Introduction

Today 89% of forests in industrialized countries and countries in transition and about 12% of the total forest area of all developing countries are considered to be managed (Wilkie et al., 2003). The area varies of course with the definition of forest management (see Box 3).

Box 3: Definition of forest management

Forest management in general can be referred to as the application of biological, physical, quantitative, social and policy principles to the regeneration, tending, utilization, and conservation of forests to meet specified goals (Sampson and Scholes, 2000). The parties under the Kyoto Protocol (KP) consider forest management "*a system of practices for stewardship and use of forest land aimed at fulfilling relevant ecological (including biological diversity), economic and social functions of the forest in a sustainable manner*" (UNFCCC, 2002). The scope of this thesis limits the definition to a set of activities that are relevant with respect to forest management for Climate Change mitigation: activities that influence carbon stocks and stock changes in forest ecosystems and forestry sector. According to the IPCC Special Report on LULUCF (IPCC, 2000) general relevant activities that likely change carbon stocks include forest regeneration, harvest quantity and timing, forest protection and elongation of lifetime of products. Forest management in this thesis will refer to activities in the forestry sector that are not afforestation, reforestation or deforestation, i.e. associated with a land-use change, but that are exclusively applied to existing forest (species choice, planting, thinning, harvest, wood extraction). An exception is Chapter Three where agricultural options are included.

Considering the properties of carbon stocks in forest ecosystems and the forestry sector and the definition of forest management above, three strategies to curb the increase of CO_2 in the atmosphere are available (IPCC, 2001a; Freibauer, 2002):

- Conservation, i.e. to prevent emissions from existing forest carbon pools. This measure has an immediate benefit for the atmosphere. Its theoretical potential equals the current existing carbon stock in forest ecosystems that could potentially be released. Conservation is important in regions with high C stocks per area.
- Sequestration, i.e. to increase stocks in existing pools. The effect of sequestration can be characterized by a slow build up following tree growth and accumulation of carbon in litter and soil. The potential of activities aiming at this effect is the carbon gain of the biosphere assuming a complete restoration up to its natural carrying capacity. Sequestration applies to areas where C stocks have been depleted.
- Substitution, i.e. to substitute energy-intensive products or products on fossil fuel basis with products based on regrowing resources. The effect as a mitigation measure is somewhat similar to benefits from conservation, and accumulates over time with each harvest and product use. The technical potential can be as high as the

emissions from fossil fuel that can potentially be substituted but always has to be seen against a theoretical reference scenario with use of fossil fuels. The effect of fossil fuel substitution depends on whether the substitution actually reduces fossil fuel use or just limits its increase. Substitution relies on harvest and therefore opposes conservation and sequestration objectives in forests.

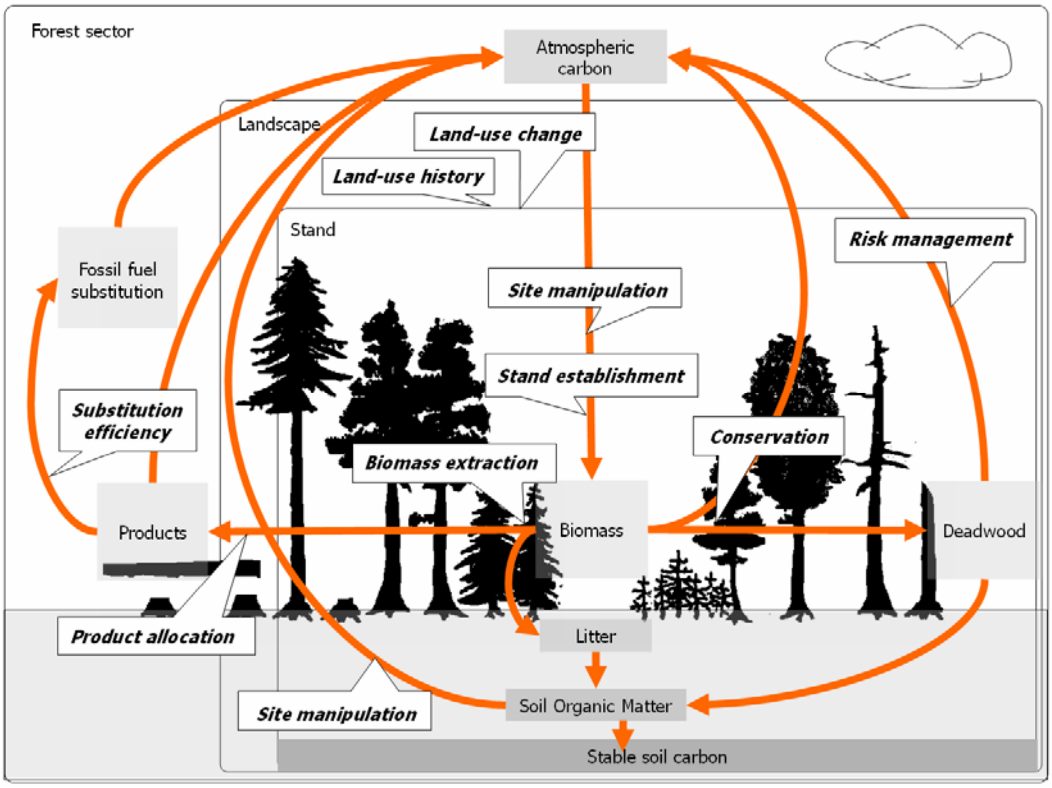


Figure 3: Overview of main effects of forest management options for mitigation. The chart shows pools and services (grey boxes), fluxes of carbon (arrows). Specific management activities are displayed as call-outs. Management activities can have multiple effects on different pools that can not all be presented in this figure.

Management of forest ecosystems can introduce and enhance sinks of CO_2 to the atmosphere through these measures as a service of atmospheric carbon mitigation. Affected pools can be biomass (above and belowground), litter, dead wood, soil organic matter, products and fossil fuel carbon substituted by products and the use of biomass for energy production (see Figure 3). Single management activities can either increase or decrease carbon pools. The effects might differ between stand and landscape level or ecosystem and forest sector perspective. The overall net-effect of management is expressed by changes in atmospheric carbon stocks. But forests are also vulnerable to climate change and carbon stocks accumulated over decades bear a certain potential of CO_2 efflux through various types of disturbances.

The first chapter is divided into two parts. The first part summarizes the current knowledge about the general potential of forest management as a measure to mitigate climate change through sequestration, conservation and substitution by analyzing the impact of forest management

- on forest carbon stocks in different pools (biomass, soil, wood products and substitution, see Figure 3)
- on different spatial levels (stand versus landscape, see Figure 3) and
- different time scales.

Part two looks into risks to the mitigation potential through human interference and a changing environment. Finally, potentials and risks are brought together in a synopsis.

ONE.2 Forest management impact on the carbon cycle

ONE.2.1 Stand level

Forest biomass

Biomass C is a pool that is often most directly affected by forest management. Rotation length, and the frequency and intensity of thinning influence stand biomass C (Kaipainen et al., 2004, Liski et al., 2001). In general, compared to unmanaged forests, the presence of management in forest ecosystems is usually expressed by a reduction of both, living and dead biomass. Table 1 stresses the major differences between presence and absence of management in different forest ecosystems. Total losses in this review turn out to be highest for conversion of natural to managed forests where original stocks are highest and management is intensive, i.e. short rotations, frequent interventions, and high C removal.

Figure 4 shows differences in carbon accumulation over time between different management regimes and carbon accumulation over time. The biomass stock increment is initially high in young forests. Assuming an undisturbed development (as in primary forests) carbon stocks of biomass increase constantly until they reach a maximum value. High stocks are accompanied with small increments. Systems under management tend to have high rates of carbon assimilation and lower total stocks due to regular disturbance and C removal by harvest. Human impacts – e.g. here biomass extraction – on biomass carbon are moderate in forests with a selective cutting regime and highest in short rotation plantations.

Table 1: Biomass carbon stocks in natural versus managed forests (WBGU, 1998).

Vegetation	Carbon stock, primary forest [t C/ha]	Carbon stock, secondary forest [t C/ha]	Age of managed forest [years]	Reduction of carbon stocks [t C/ha]	Reduction of carbon stocks (%)
Temperate forests					
Natural forest of Pseudotsuga-Tsuga vs. Pseudotsuga plantation, Canada	433	192	60	241	57
Deciduous broad leaved forest vs. plantation, Europe	380	230	80	150	39
Natural beech forest vs. managed beech forest, Slovakia	290	137	150	153	53
Boreal forests					
Natural pine forest vs. managed pine forest, Finland	190	99	101 - 150	91	48
Natural spruce forest vs. managed spruce forest, Finland	169	93	101 - 150	76	45
Natural birch forest vs. managed birch forest, Finland	130	78	101 - 150	52	40
Tropical forests					
Moist forests vs. secondary forests	273	127	18	146	53
vs. plantation, Africa/ America	273	155	20	118	43
Dipterocarpaceae forest vs. secondary forest	333	127	18	206	62
vs. plantation, SE Asia	333	155	20	178	53
Seasonal forest vs. secondary forest	141	77	18	64	45
vs. plantation, SE Asia	141	82	20	59	42

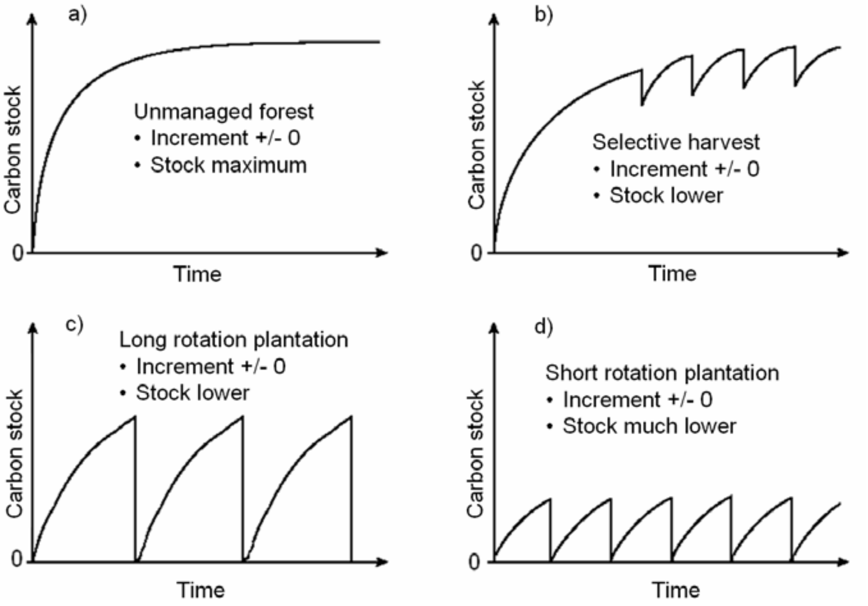


Figure 4: Schematic carbon stock development of aboveground biomass under different management systems (redrawn from WBGU, 1998).

In many forestry regions forest stands are thinned, leading to early revenues and distributing site resources to fewer individual trees. Optimal timing and thinning intensity increases the volume of individual timber compared to unthinned stands (Nyland, 1996). However, at stand level thinning reduces tree density. Depending on species, below a critical level of stand density the remaining trees cannot compensate for the crown cover of the removed trees at the stand level (Assmann, 1968). Between well-timed thinning operations the number of trees does not change. This leads to reduced losses to natural decomposition and leaves more carbon for harvest, wood products and substitution.

On sites, where nutrients and water are limiting, the potential to enhance and accelerate biomass production and yield through fertilizer application and irrigation might be large (e.g. Nilsson, 1997; Stromgren and Linder, 2002, Bergh et al., 2005) even in the long term (Pettersson and Hogbom, 2004). However, the question whether fertilization also results in enhanced long-term C sequestration is less clear and probably only valid for some cases (Adams et al., 2005).

Forest soils

Land-use change induced effects on soil carbon storage, e.g. induced by afforestation, have been analyzed in various studies (cf. Paul et al., 2002, Guo and Gifford, 2002). Model results indicate that also soils in existing forests can be a strong sink for carbon (e.g. in Europe as reported by Liski et al., 2002). The rate of soil carbon sequestration, and the magnitude and quality of soil C stocks depend on the complex interaction between climate, soils, tree species, litter quality and management (Lal, 2005a). Effects of forest management on soil conditions in terms of nutrient removals in harvested timber, canopy removal with accompanied microclimatic changes and chemical and mechanical site manipulations are evident in most forest types (e.g. Ballard, 2000).

Several reviews exist that analyze the experimental evidence for long-term carbon storage in soils through specific forest management strategies (Johnson, 1992; Johnson and Curtis, 2001; Lal, 2005b; Jandl et al., 2007). Jandl et al. (2007) analyzed the effects of harvesting, thinning, fertilization application, drainage, tree species selection, and control of natural disturbances on soil C dynamics and stressed the importance of differentiation between effects on labile and stable soil C fractions. They conclude that the C storage capacity of the stable pool can be enhanced by increasing the productivity of the forest and thereby increasing the C input to the soil. However, increased tree growth does not necessarily also increase soil C (Shan et al. 2001).

Experimentally, soil carbon changes and effects of forest management on carbon storage are hard to detect due to relatively slow processes and a high temporal and spatial heterogeneity. In addition, effects of recent management or management changes are often interfering with effects of factors like site conditions, climate and land-use history (Mund, 2004). Mund and Schulze (2006) found that effects of disturbances due to different silvicultural harvest methods on soil carbon were comparably small considering a high small-scale variability of soils and potential long-term effects of historical forest use. They state that a major challenge of future research would be to quantity the long-term effects of historical forest use on soil carbon stocks and to separate them from the effects of recent forest management. C stocks depend more on soil texture and land-use history rather than on recent forest management in long-term established forests (Wirth et al., 2003; Mund, 2004). Similar conclusion are presented by Yanai et al. (2003) who explain observed differences in carbon stocks in stands of different ages with changes over time in logging technology and the intensity of biomass removal. The fate of carbon in litter and harvest residues depends on the balance of mechanisms that release carbon to the atmosphere and those that transfer it to the mineral soil that need to be distinguished.

Johnson et al. (2002) found that differences in litter carbon triggered by different treatments of logging residues do mainly contribute to short-term differences in soil carbon. The mineralization rate of soil C depends to a large extent on litter quality and thus tree species (Giardina et al., 2001). The choice of tree species for a certain site is a management decision and can influence C storage in soils in the long run (Binkley and Menyailo, 2005).

It is also not completely clear whether there is a maximum C carrying capacity of soils or not in absence of disturbance, as ecosystems are typically subject to disturbance that periodically reduce C stocks (Schulze, 2006). In fact, effective soil carbon management needs to focus on minimizing forest disturbances of stand and soil stocks to reduce the risk of unintended C losses (Jandl et al., 2007).

Harvested wood products and fossil fuel substitution

The carbon balance of a forest landscape can be extended to the forestry sector level by including harvested wood products (e.g. Liski et al., 2001). Production of wood products is the primary function for 34% of the world's forests. Global wood removals were estimated to amount to approximately 0.8 Gt of carbon in 2005 (FAO, 2005), similar to the total removals recorded for 1990. The amount of wood fuel harvested is more than one third of it. Products affect the carbon cycle in three major ways (IPCC, 2001a):

- as a physical pool of carbon, built up by harvest, maintained through recycling, and depleted by decay
- as a substitute that replaces fossil fuel and energy-intensive materials
- as an energy source.

Thinning or harvest operations replace natural mortality in a forest ecosystem partly, and result in wood products that contain a certain part of the carbon originally stored in biomass. Taking wood products as a carbon pool into account can resolve the conflict between wood production and carbon sequestration, that has often been reported (e.g. Fischlin, 1994), at the annual time scale. The issue is not resolved as the residence time of C in products changes, too. But it brings C fluxes closer to reality than the purely ecosystem-centered view of the UNFCCC and the Kyoto Protocol (see Chapter Three).

Removals, used for sawn-wood and wood-based panels have a high proportion being used in permanent constructions, which means that the carbon stored in the wood is bound in these materials over decades. Other products, like fuel wood and paper, keep the carbon stored for a few years at maximum. The IPCC Third Assessment Report on Mitigation (IPCC, 2001a) lists four options that influence the effect of carbon in wood products:

- Level of production of wood products, increase/decreasing the pool size
- Change in quality of wood products, lifetime changes
- Changes in processing efficiency
- Changes in recycling rates and fate of wood products

Including the storage of carbon in harvested wood products with associated substitution effects can, but do not have to improve mitigation services of the forestry sector (Nabuurs and Sikkema, 2001). The use of bioenergy from biomass to substitute for energy from fossil fuels will increase further. Net effects depend on substitution efficiency, i.e. on how bioenergy is produced, on the type of energy that is substituted and on the extent of displacement (Schlamadinger and Marland, 1994).

ONE.2.2 Landscape level

In general, the effectiveness of mitigation activities at the landscape level depends on the initial status of the ecosystem, and the fractional cover of the various forest stages in the landscape. For degraded areas without closed tree cover restoration permits large C gains per hectare (Figure 5). Primary forest protection yields in relatively small sequestration rates, but offers mitigation potential through carbon stock conservation, which, however, is not yet fully included under the Kyoto Protocol.

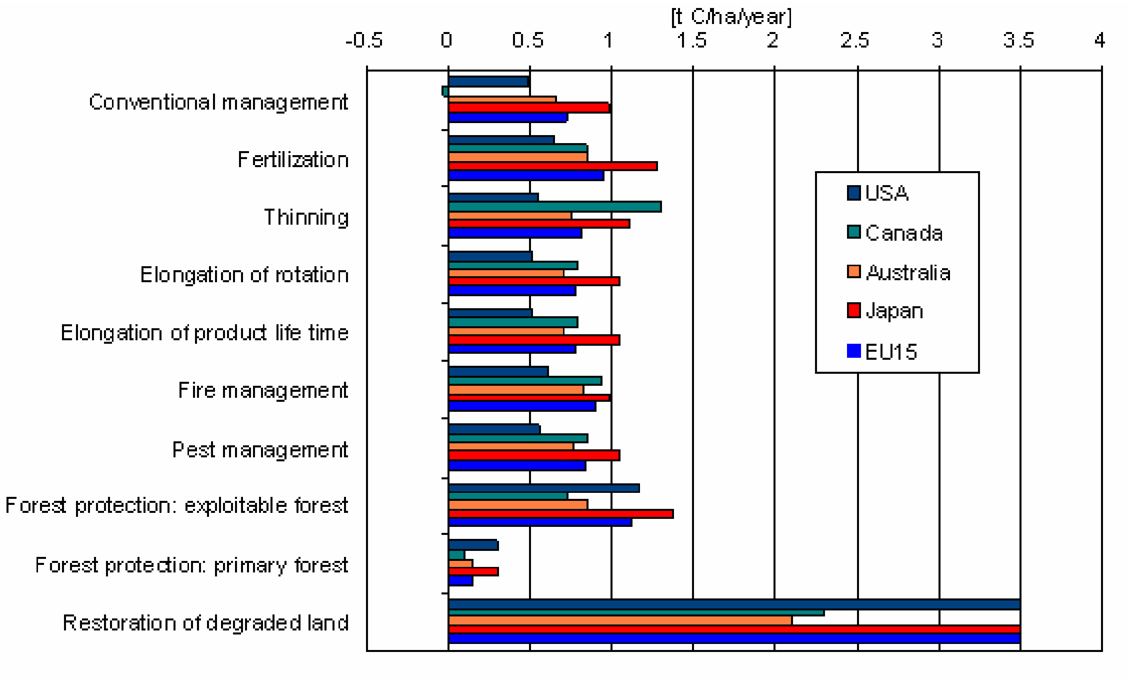


Figure 5: Total potential sequestration per hectare for different forestry activities (adapted from Nabuurs et al., 2000).

An important key to projecting carbon dynamics of managed forests lies within their initial age structure (Alexandrov et al., 1999). A certain management, e.g. described by length of rotation, applied to a forest landscape can have different consequences for landscape carbon stocks. The response to the applied management, whether the landscape will act as carbon source or sink, is prescribed by the age-class structure. The age-class structure, on the other hand, is mirroring past management and stand replacing disturbances. The principles laid out in the Marrakech Accords (see Chapter FIVE.1) for accounting of C sinks by land-use activities require to factor out such effects that might lead to a situation where two countries, despite the fact that they apply the same management, account for stock changes in opposite directions. Chapters Five and Six of this thesis examine how forest carbon stock changes which result from past forest management can be identified and accounted for. Whether or not and how to separate the effects of past and present management on forest C stock changes is yet unsolved in science and climate policy.

ONE.3 Risks opposing mitigation potentials

ONE.3.1 Climate change feedbacks

Global fluxes of carbon between atmosphere and terrestrial ecosystems can be induced and altered either by natural or by direct or indirect human-induced influences. Processes related to the latter include atmospheric and climate variability and change such as CO_2 fertilization, N fertilization by N deposition, plant growth suppression by air pollution and changes in plant production or soil respiration due to climate change and climate variability (Canadell et al., 2007a). Current knowledge attributes a certain share of the observed forest sink to such indirect human-induced effects (Schulze, 2006; Canadell et al., 2007a; Canadell et al., 2007b).

But predicted changes in climate have also raised concerns about potential impacts on the strength and permanence of the observed terrestrial C sink in the Northern Hemisphere (Ciais et al., 1995; Ciais et al., 2005). In fact, besides atmospheric phenomena like the Southern Ocean circulation a main source of the uncertainty is the response of vegetation and soil carbon to global change (Friedlingstein et al., 2003). Despite differences in the magnitude of response, global vegetation models coupled to climate models show a positive feedback between climate change and the carbon cycle of terrestrial ecosystems, i.e. climate change is likely to cause additional CO_2 emissions from these systems. Some simulations of coupled models expect that the biosphere will turn into a source in the next decades (Cox et al., 2000; Cox et al., 2004). Carbon storage by the land biosphere becomes thus more uncertain. Other estimates (Schaphoff et al., 2006) ranged from -106 to +201 Gt C by the end of the century, revealing, that even the sign of the response, whether the terrestrial biosphere will be a future source or sink, is uncertain.

Climate change will also increase climate variability and most probably lead to more frequent and severe extreme weather conditions (IPCC, 2001b, , 2007). Just recently a joint effort compiled measurements of ecosystem CO_2 fluxes, remotely sensed radiation absorbed by plants, and country-level crop yields recorded during the European heat wave in 2003 and compared them to modeled data (Ciais et al., 2005). July temperatures in 2003 were up to 6 degrees C above long-term means, and annual precipitation deficits up to 300mm per year, 50% below the average. The group estimated a 30% reduction in GPP over Europe, which resulted in an anomalous net source to the atmosphere, i.e. compared to 'normal' conditions the sink capability of the European terrestrial biosphere was reduced significantly.

Forests are vulnerable to climate change. There is an overall agreement that climate change will have a feedback on both, single processes in plants and large-scale forest dynamics. Independent from the question 'sink or source': climate change leads to an increased exchange of CO_2 due to increased metabolic activity and higher turnovers. The rate of change in climate variables is important: damages and shifts in the C balance are especially caused when there is a) a rapid change and b) a large change exceeding tolerance boundaries for water and temperature. As an effect of a climate change feedback the response could result in a considerably lower carbon sequestration rate or even a switch to a net source, both leading to a faster increase of the airborne fraction of CO_2 in the future and diminishing the potential of forests and the forestry sector for climate change mitigation.

ONE.3.2 Natural disturbances

Besides natural breakdown (tree death) and harvest, C emissions tend to result from disturbances (storms, fire, and pest outbreak). Unlike disturbances like insects and storm, forest fires have the potential to release large amounts of CO_2 within a short period of time. In a fire, carbon accumulated over decades may be emitted within a few hours (Körner, 2003). In many ecosystems of the world forest fires occur regularly representing a natural disturbance and strongly influencing biomass accumulation. In these regions, like the boreal forests of Siberia, climate change may affect ecosystem functions predominantly via changes in fire regimes (e.g. Wirth et al., 1999).

Disturbance regimes are not only indirectly changed through human activity. Mollicone et al., 2006 examined the number of forest-fire events across the boreal Russian Federation for the period 2002 to 2005. They separated forest area into 'intact' forests, where human influence is limited, and in 'non-intact' forests, which have been shaped by human activity. The results show that there were more fires in years during which the weather was anomalous, but that more than 87% of fires in boreal Russia were likely to have been started by people.

While the area affected by forest fires in temperate and boreal forests is currently decreasing, burned areas increased exponentially in tropical forests, reaching 54 Mha per year in the 1990s (Mouillot and Field, 2005). According to the authors, this increase reflects the use of fire in deforestation for expansion of agriculture. Severe fire events in tropical regions like in the Indonesian peat forests in late 1997 were caused by extreme drought conditions e.g. resulting from El Nino anomalies (Siegert et al., 2001). However, forest fires primarily affected recently logged forests. Human activity is thus also one of the largest uncertainties for many so-called 'natural' disturbances. It can both enhance and suppress disturbances such as fires through anthropogenic ignition, fire suppression and fire management by timber exploitation and debris abandonment (Ito, 2005). Climate change feedback effects and natural disturbances are beyond the scope of this thesis. However, the potential mitigation contribution of forest management has to be seen in the perspective of changing environmental (but also economical) conditions.

ONE.4 Concluding thoughts on mitigation potentials

It is evident that a forest carbon sink is limited due to the nutrient-limited carrying capacity of forest stands and that natural disturbances bear the risk of losses. Still, there seems to be a huge theoretical potential for carbon storage through afforestation, establishment of close to nature forestry and refilling depleted soil carbon reservoirs. Past degradation and continued human need for resources from land, however, makes part, if not most of this biological potential unrealistic. The term 'potential' is thus ambiguous. The magnitude of the carbon source and sink potential varies along with the types of constraints considered (IPCC, 2001c; Hargreaves et al., 2003):

- Biological potential is the theoretical biologically achievable capacity, meaning that some or all practical constraints have been ignored.
- Technological potential is the biological capacity constrained by suitability of land and availability of resources and technology. Assumptions about land availability, socio-economic and policy drivers are optimistic.
- Economic potential describes a conservative technical potential taking into account costs, with some optimistic assumptions about social barriers, incentives and speed of implementation of measures.
- Realistic potential can be defined as a short-term capacity taking into account the economic potential plus social barriers, present policies, presence or lack of incentives and the competition of different land-uses.

Recent studies suggest that 10-20% of the biological potential are economically achievable within the next 10-50 years in case of strong incentives (Hargreaves et al., 2003;

Schneider and McCarl, 2006; Smith et al., 2007). The examples in Table 2 demonstrate that estimates of carbon sequestration potentials are highly sensitive to the region, time frame and assumptions included in the calculations.

Table 2: Cascade of potentials in agriculture and forestry in recent literature. N.E. = Not estimated. *) Sum of C sequestration and bioenergy in agriculture and forestry; References: 1) Watson et al., 2000; IPCC, 2001c; 2) Hargreaves et al., 2003

Region	Time horizon [years]	Biological potential [Mt C yr^{-1}]	Technological potential Tg C yr^{-1}]	Economic potential [Tg C yr^{-1}]	Realistic potential [Tg C yr^{-1}]	Biological cumulative capacity [Pg C]	Reference
Globe	40	1500-2100	1500-2100	N. E.	N. E.	100-140	1)
Globe	50-100	1900-4900 *	950-1900 *	190-950 *	N. E.	100-200	2)
EU-15	50-100	190-490 *	50-100 *	20-50 *	N. E.	20-30	2)

Carbon sequestration in the LULUCF sector is to a large degree a non-permanent strategy. Tree plantations that are established, harvested but not re-established do not contribute to carbon sequestration. The sequestration phase is finite, lasting for some decades and gained carbon stocks need to be protected thereafter to keep carbon withdrawn from the atmosphere. Sequestration therefore always needs to be guarded by conservation measures to make mitigation strategies effective. Implications on stand and landscape levels have to be considered. Future estimates of sequestration potential need to be well constrained by economic and social borders to be realistic.

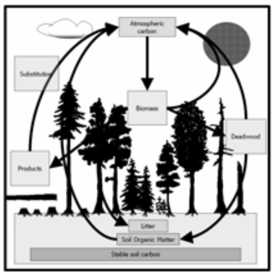
Future projections of the forest carbon sink largely depend on other scenario parameters, especially future human land-use. Forest ecosystems of the world are considered as multifunctional, supplying timber, non-timber products, fresh water, and space for recreation or wildlife. Since the day scientists suggested that the terrestrial biosphere is currently gaining carbon from the atmosphere, C sequestration became an additional ecosystem service (e.g. Dixon et al., 1994; Ciais et al., 1995). But land is a precious and finite resource. Not only the potential sequestration capacities need to be well constrained to realistic estimates, but human activity is also likely to put the gained stocks at risk again (Table 3). There is overall consensus about the prevailing effect of human activities that may superimpose all climate change effects on changes in the terrestrial C balance.

Table 3: Sink capacity and threats of global carbon pools in Gt C. Threats are caused by harvest, deforestation, forest management, browsing and other land-uses and land-use changes, as well as more frequent fires (Gruber et al., 2004). The risk of carbon release does not necessarily have to take place at the same location or pool.

Pool	Stock	Sink capacity		Threat	
		in 20 years	in 100 years	in 20 years	in 100 years
Soils	3150		300	10	400
Living biomass	650	40	150	50	200
Total	3800	40	450	60	600

TWO

DESCRIPTION OF FORMICA – A GENERIC CARBON BUDGET MODEL OF THE FORESTRY SECTOR



TWO.1 Introduction

A major conclusion from the findings from Chapter One and a motivation for this thesis is the observation that a large part of the observed current forest sink in the Northern Hemisphere is caused by past and recent forest management and might thus be manageable itself. To realize more C sequestration in forests as a tool for climate change mitigation, it is necessary to better understand impacts of forestry practices on the C balance, so that appropriate forest management strategies can be developed to reduce atmospheric CO_2 concentrations. The FORMICA (FORest Management Impact on CArbon dynamics) model, a dynamic inventory-based carbon-tracking model, which is capable of tracing forest carbon pools in managed forest ecosystems and the adjacent forestry sector, is introduced in this chapter.

Recent literature on forestry models suggests that empirical models remain strong tools in terms of applicability and accuracy, despite their lack of predictive power under changing growth conditions (e.g. Porté and Bartelink, 2002; Landsberg, 2003; Mohren, 2003). A comprehensive empirical model of the entire forestry sector was introduced with the GORCAM model (Schlamadinger and Marland, 1996). It traces C stocks and flows associated with management of forests or agricultural land. The model calculates C accumulation in biomass, soil, in product pools of different turnovers and finally in fossil fuels not burned because generation of products that are made from wood instead of other materials requires less energy, and in fossil fuels substituted by bioenergy. So far the GORCAM approach focused on the plot level only for the comparison of different options but not on a landscape level. However, the key to projecting carbon dynamics of forests lies within their age structure (Alexandrov et al., 1999) and this requires a regional application of the forestry model.

To explore consequences of changes in forest management, large-scale scenario models have been developed to combine forest inventory data and forest growth models (Mohren, 2003). Since ground-based forest inventories are not available globally, such a model needs to be applicable to remotely sensed biomass inventories as well. The FullCAM model integrates process-based models to describe single-tree growth, decomposition and soil processes at stand and landscape scales (Richards, 2001). This model is one of the most ambitious tools for carbon accounting in Australian plantations. Kurz and Apps (1999) developed a model for carbon accounting in the Canadian forestry sector (CBM-CFS) including fire disturbances and the wood product sector. The operational scale C budget model CBM-CFS2 represents another detailed tool for studies of C dynamics and mitigation strategies in managed forests (Kurz et al., 2002). The European Forest Information Scenario Model (EFISCEN) is a large-scale matrix model, which compiles information on forest resources in Europe and produces projections of the possible future development of forest resources and carbon stocks (Pussinen et al., 2001). However, due to their structure, matrix models cannot capture growth dynamics at the stand level following biomass extraction. There is still the need for a dynamic forest management model that can easily be combined with forest inventories and applied to possible future management scenarios. The CO2FIX approach (Masera et al., 2003) is an attempt towards a general model structure for estimates of carbon sequestration through forest management, agroforesty and afforestation but it is limited to project-level calculations.

A model is an approximation to the real world and is usually designed for a more or less distinct purpose and application. It should not be applied beyond its designated scope, range of conditions and scale of operation. In general, the broader the conditions and the wider the range of scale, the more detailed are the required model inputs and represented processes. The wide range of scientific questions posed in this thesis (see Introduction) can hardly be answered by pure application of one of the existing models presented above. The model needs adaptation to each of the questions. The model structure needs to be both, flexible and comprehensive. Further, the rules and algorithms implemented in the model need to be transparent and simple to allow for interpretation. The development of such a model is the aim of this chapter of the thesis.

TWO.2 Model description

The model FORMICA aims to calculate carbon pool trajectories under current and changing forest management in existing forests at a regional scale. The basic structure of FORMICA is summarized in Figure 6. The model captures the development of the current annual stem wood increment and the allocation of biomass to branches, foliage and roots. Underlying data and parameters are displayed as broad arrows. The large boxes represent different model modules.

FORMICA considers forest biomass to be an entity of mass in different compartments and it ignores single trees or layers. Increment of stem biomass is related to stem biomass accumulated. Net primary production (NPP) and net growth of other compartments than stem is described indirectly through the allocation function: stem biomass translates through the allocation function into biomass of branches, roots and foliage. The change in these biomass compartments in subsequent time steps is considered as compartment net production. The losses induced by compartment turnover are added to net production, resulting in NPP. Biomass harvest can be parameterized to various forest management activities like planting, thinning and final harvest as clear cutting, shelter wood or continuous cover forestry. Treatment is simulated by removing fractions of stem biomass and channeling material that is left in the forest to according litter pools.

Soil and litter pools are important components of the forest ecosystem balance and are included in the FORMICA frame through an implementation of algorithms of an existing model (Liski et al., 2005). The lifetime of wood products and possible substitution effects of wood by other materials has a strong feedback on the C balance of the forestry sector. Therefore, the model offers options to transfer C from biomass to different product pools characterized by mean residence times in a forest product module.

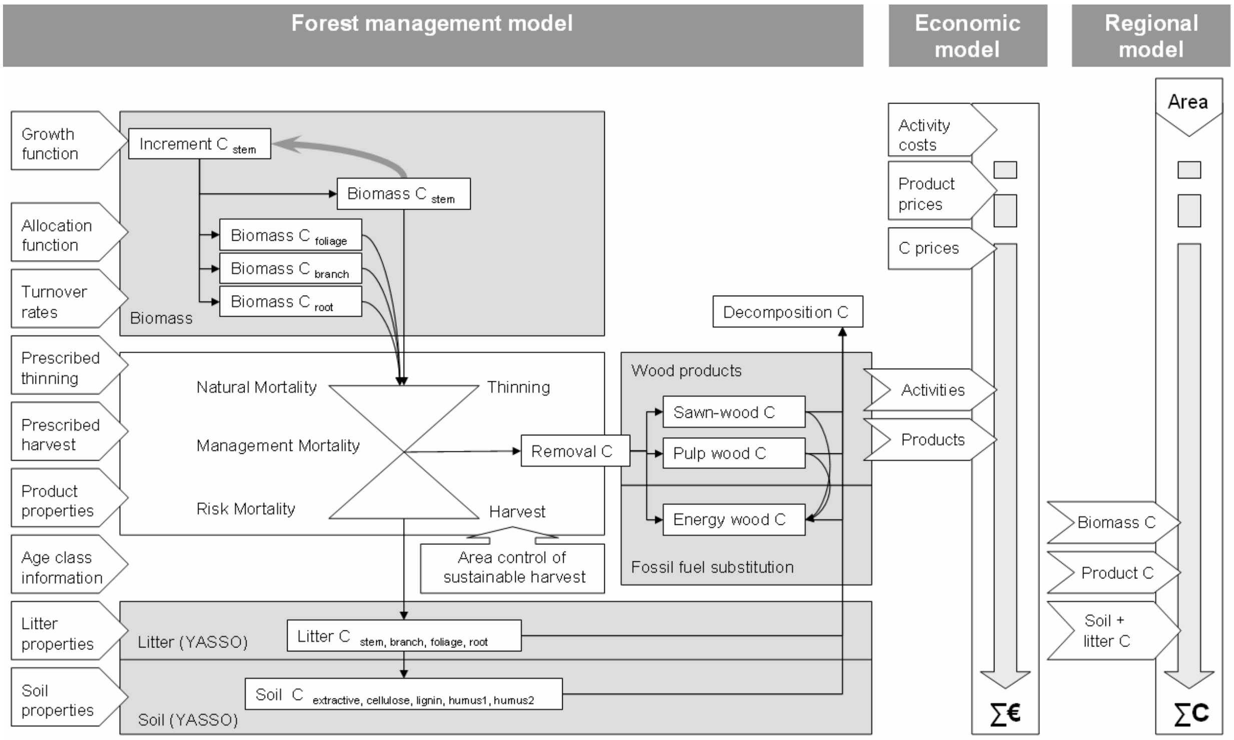


Figure 6: Simplified overview of FORMICA structure. Grey boxes delineate modules incorporated in the model structure, broad arrows describe major input data and parameters, small arrows sketch the flow of carbon between compartments.

An economic module was introduced to investigate economic implications of different forestry options. The algorithms that were implemented sum revenues and costs of forestry activities and allow for the calculation of a discounted net present value (NPV) of each option.

Finally, a regional model allocates pools and considered management options to designated areas and age-classes and summarizes FORMICA model results. Calculations are based on an annual time step. The programming language is Matlab, by MathWorks, Inc., model source code is provided on CD-Rom attached to the thesis.

TWO.2.1 Biomass module

The main features of the biomass module are:

a) the use of parameters that can be derived from general forestry statistics or national/regional forest inventories,

b) allowing for a variety of management intensities as applied in managed forests including various thinning regimes,

c) the use of growth relative to standing volume and allocation functions depending on accumulated stem biomass. This allows applications on a wide range of forest eco- and management systems including uneven-aged, multilayered and natural forests. The following equations are used:

Stem increment in the current year is expressed by following Vanclay's (1989) approach of relative plant growth. Stem annual increment AI_S is a function of last year's stem volume V_S remaining in the stand, following Equation 1:

$$AI_{S\ t} = \alpha_0 + \alpha_1 * V_{S\ t-1} + \alpha_2 * \log(V_{S\ t-1}) \qquad (1)$$

, where a_0, a_1 and a_2 are species- and site-specific coefficients. Appendix, Table A1 lists parameter values applied for various species. Translated to carbon, AI_S refers to stem net primary production (stem NPP). The rate of stem volume increment depends on how much volume is left from the last period. By initializing a certain stem volume after harvest, the model simulates planting ensuring a fast regrowth. Natural regeneration after the entire biomass is removed is controlled by intercept a_0.

To be applied for regional growth modeling of various cohorts and species, parameters a_1 and a_2 of Equation 1 need to be estimated from inventory data or yield tables. We used the first derivative of the equation to determine $AI_{S\ max}$, i.e. the maximum increment of the growth function. The parameters a_1 and a_2 can then be substituted by the following:

$$\alpha_1 = -\frac{\alpha_2}{\ln(10) * V_{AI\,S\,\max}} \tag{2}$$

$$\alpha_2 = \frac{1}{\frac{-1}{\ln(10) * AI_{S\,\max}} + \log 10(V_{AI\,S\,\max})} \tag{3}$$

, where $V_{AI\ S\ max}$ is the volume at $AI_{S\ max}$. The growth function (Equation 1) can by this means be parameterized more conveniently through determining the maximum increment during the lifetime of a stand or cohort and the volume at which this occurs, both site- and species-specific parameters.

To estimate growth of compartments other than stem (foliage, branches and roots) FORMICA uses generic biomass functions and expansion factors (Equations 4 – 8). Equations by Wirth et al. (2004) are used for spruce (Picea abies) to calculate biomass *B* of each compartment *i*:

$$EF_i = \beta_0 + \beta_1 * e^{-\beta_2 * V_S} \tag{4}$$

$$B_i = EF_i * B_S \tag{5}$$

, where *EF* is the expansion factor of a compartment, β_0, β_1 and β_2 are compartment-specific coefficients, B_S is stem biomass and V_S is stem volume. For Scots pine (Pinus sylvestris), biomass functions of Lehtonen et al. (2004) based on biometric measurements from Swedish forests were used:

$$B_i = e^{\beta_0} * V_S^{\ \beta_1} \tag{6}$$

, where β_0 and β_1 are compartment-specific coefficients and V_S is stem volume. Allocation of deciduous trees (here beech and oak) for foliage (index *F*) and roots (index *R*) is taken from a global analysis by Enquist and Niklas (2002):

$$\log(B_F) = \beta_0 + \log(B_S) * \beta_1 \tag{7}$$

$$\log(B_R) = -\beta_0 + \log(B_S)/\beta_1 \tag{8}$$

, where β_0 and β_1 are compartment specific coefficients.

Four different mortality components are included in the model. To estimate losses through natural mortality due to aging (*AM*) of each plant compartment *i* a simple turnover rate was introduced, independent of forest age:

$$AM_i = \gamma * B_i \tag{9}$$

, where γ is a compartment and species-specific turnover rate and *B* the accumulated biomass of a compartment *i*. The algorithm is applied to estimate branch, foliage and root mortality separately.

To calculate net growth (stem NEP) at stand level losses due to competition between plants through increasing vegetation density has to be taken into account (in the following referred to as "density mortality"). The model does not simulate the development of stand density explicitly. FORMICA considers an approach including an ecosystem specific maximum biomass $B_{S\ max}$. Density mortality *DM* is a fraction of stem increment AI_S relative to how close the actual stem biomass B_S of the system is to the maximum value:

$$DM_S = (B_S / B_{S\max}) * AI_S \tag{10}$$

Density Mortality is suppressed if stem biomass has been already reduced through human activities, e.g. thinning:

$$DM_S = \frac{\left(B_S - B_{S\,ThinningYear}\right)}{T_{ThinningYear}} * (B_S / B_{S\max}) * AI_S \tag{11}$$

, where $T_{ThinningYear}$ is the volume removed during and $B_{S\ ThinningYear}$ the amount of stem biomass before the last thinning. The fraction lost to density mortality of the remaining compartments is DM_S/B_S.

A third type of mortality is related to management (*MM*) and describes losses additional to harvest. These include carbon losses by injured and dying trees after intensive logging, which are calculated by the approach presented in Masera et al. (2003). The algorithm transfers annually a prescribed amount of biomass for a prescribed period of time to the litter pool. The fraction of biomass affected by management mortality depends on tree species, harvest type applied, and amount of biomass extracted through previous harvest.

Forest stands face a risk to various hazards like storms, insects and fire. Kouba (2002) used the following form of the Weibull function to calculate a survival rate *R* dependent on stand age *a*:

$$R(a) = 1 - F(a) = e^{-\lambda * a^{\kappa}} \tag{12}$$

, where *ϰ* and *λ* are coefficients to be estimated and *F* the fraction of trees surviving. To avoid R to become zero, an asymptotic elimination rate *c* is introduced:

$$R(a) = (1 - c) + c * e^{-\lambda * a^{\kappa}} \tag{13}$$

Forest mortality due to wind (*RM*) is the compartment biomass in the year *a* multiplied by R. The litter fall *(LF)* of one year in a compartment *i* is the sum of every source contributing to the litter:

$$LF = \sum_{i=1}^{n} MM_i + AM_i + DM_i + RM_i + S_i \tag{14}$$

, where *MM*, *AM*, *DM* and *RM* are litter inputs from management, natural, density and risk mortality and *S* (slash) is residual material from harvest and thinning.

TWO.2.2 Soil module

Litter is transferred to the soil model YASSO (Liski et al., 2005) which requires these litter inputs data besides basic information on climate and litter quality information. The model is based on five assumptions that need to be taken into account when applying the model and interpreting results: 1) litter and soil organic matter consist of different compound groups, which decompose at typical rates, 2) decomposition of woody litter does not only depend on its chemical composition because it is not exposed to microbial decomposition immediately, 3) decomposing compounds lose a certain proportion of their mass per unit of time, 4) a part of the decomposed mass is removed from the soil as heterotrophic respiration or leaching while the rest forms more recalcitrant compounds, 5) Microbial activity depend on favorable temperature and moisture conditions (Liski et al., 2005).

YASSO consists of five decomposition compartments and two litter compartments. The rates of decomposition and invasion of woody litter by microbes are controlled by temperature and summer drought. The model is applicable to different ecosystems and climate conditions (Liski et al., 2005).

TWO.2.3 Product module

Harvested wood products are represented in FORMICA through three pools. Allocation to them is dependent on species and size of timber expected from harvest. The pools differ in the average time they retain C before it is either released to the atmosphere or recycled to another product pool. Two pools treat products of long and short lifespan, a third pool traces wood harvested for energy production (Table 4).

Table 4: Example of different wood products with mean residence times (MRT) according to Wirth et al (Wirth et al., 2003) and grouping in FORMICA product module.

Product pool in FORMICA	Products	MRT [years]
Wood products with long lifespan	furniture, particle board, chipboard, fiberboard	25
	parquet wood	43
	construction wood	51
Wood products with short lifespan	pulpwood	1
	wood for packing material, wood for temporary constructions (building sites)	3
Energy wood	biomass for bioenergy, fire wood	1

TWO.2.4 Economy module

With the help of an economy module FORMICA can be used to investigate economic implications of different forestry options. The algorithms that were implemented sum revenues and costs of forestry activities and allow for the calculation of a discounted net present value (NPV) of each option. Annual costs and revenues are discounted using the following algorithm:

$$C_{t0} = \sum C_{i,t} * \exp(-\rho * t) \tag{15}$$

, where $C_{i,t}$ are the costs for an activity or revenue for a product i at point in time t and ϱ is a discount factor.

Annual revenue can be achieved with the sale of harvested wood as sawn timber, pulp or energy wood but also through subsidies and premiums. For both, carbon sequestered in the forest ecosystem and harvested wood products but also for carbon emissions from fossil fuels substituted with bioenergy payments can be claimed on a carbon market with prescribed prices. Costs can either be associated with timber volume (harvest and extraction costs) or with area (planting costs).

TWO.2.5 Regional C budget model

To estimate a regional C budget, FORMICA calculates first the carbon pool trajectories at the plot-level. Those are computed for different strata, i.e. a combination matrix of age/biomass classes, management options, species and production levels. The total biomass of all compartments within a stratum *k* remaining after one period is then calculated as:

$$B_k = \sum_{i=1}^{n} \left(AI_i - T_i - H_i - MM_i - AM_i - DM_i - RM_i \right) \qquad (16)$$

, where T and H are losses to thinning and harvest, respectively. In a second step the model aggregates plot-level calculations of fluxes and stocks to the regional C budget, accounting for the actual uneven distribution of species, age-classes and management regimes through different strata. The total amount of biomass of a compartment of a region is estimated as:

$$B_{Region} = \sum_{k=1}^{n} B_k * Area_k \qquad (17)$$

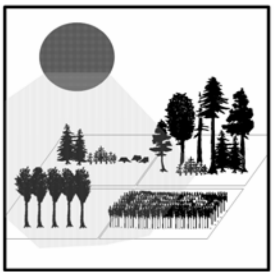
, where *k* represents one stratum and *Area* the area related to a certain stratum.

Another aspect of the regional model covers the issue of continuous timber flow. Forestry activities, especially timing of harvest is (besides forest growth) to a large degree controlled by market conditions. To model future harvest events simply by a fixed calendar of events like prescribed rotation lengths would result in a too deterministic approach. Since harvest would be just driven by stand age, an age-class structure underlying a landscape that is treated under such conditions would not change. It would be carried through the simulation time creating a regular source sink pattern on a long-term scale. One way to introduce a market mechanism to account for economic behavior is the implementation of a periodical allowable cutting level. To establish it, the model first determines the 'Normal Forest' area for each management option, which is the forest area under management in a certain option divided by rotation length and multiplied by age-class width. In such a 'Normal Forest' landscape every age-class under management covers the same area and therefore each period the same amount is harvested. It is a forest structure that supplies continuously the same amount of wood and is thus sustainable from the production's point of view.

The age-class structure of a real forest landscape diverges from the ideal concept of a 'Normal Forest'. But the concept can be used as a basis for modeling sustainable forest management. The rule introduced in FORMICA allows harvest of trees only under two conditions: the current stand age is above or equal to harvest age and the harvested area in the current period is equal to or less than the 'Normal Forest' area in this age-class. This guarantees a continuous timber flow on a sustainable basis simulating a constant demand function in an open market.

THREE

OPTIMAL LAND MANAGEMENT FOR BALANCING CLIMATE CHANGE MITIGATION BENEFITS AND LAND-OWNER REVENUE



THREE.1 Introduction

To date, no general consensus has been reached on how to measure the effectiveness of climate change mitigation in the land-use sector. The accounting rules under the Kyoto Protocol favor an ecosystem centered short-term perspective and exclude changes in the wood product pool. The effect of fossil fuel substitution is implicitly reflected in lower emissions from the energy sector. The value of carbon already stored in ecosystems and related ecosystem services have so far been disregarded. However, carbon stored on land can be lost by human action through harvest or removal of vegetation, the shift of forestry to shorter rotations and shorter lived products (Sohngen and Brown, 2006) and land degradation, or unwittingly through forest disturbance (Kurz and Apps, 1999) or soil processes (Bellamy et al., 2005). Ecosystems can lose carbon much faster than they accumulate (Körner, 2003) so that the protection of existing carbon stocks in ecosystems constitutes an alternative effective mitigation strategy. Only wider system boundaries reflect the true GHG performance of ecosystem management in a specific regional context as a basis for decision making. Decadal to centennial time scales reflect whether the climate effects of land management reverse, level off or accumulate over time. Analysis of the full life cycle and the reuse during cascades of ecosystem products explicitly includes the substitution of energy intensive products and fossil energy carriers by renewable raw materials (Marland and Schlamadinger, 1997; Gielen et al., 2001; Dornburg and Faaij, 2005; Perez-Garcia et al., 2005; Petersen and Solberg, 2005).

There is no one-fits-all strategy for optimal land management (Marland and Schlamadinger, 1997). The solution will consist of a mix of land-use and management systems adapted to the regional mosaic of geographical and economic constraints and the diversity of markets. Existing studies have focused on large-scale mitigation potential (Gielen et al., 2001; Schneider and McCarl, 2003), theoretical projects (Garcia-Quijano et al., 2005), or partial aspects of forestry such as carbon removal versus timber (Bateman and Lovett, 2001; Backeus et al., 2005) and bioenergy production (Cheng et al., 2000; Kirschbaum, 2003). None of the studies covers forestry together with agricultural options at the regional level where most of the operational planning and competition for land takes place.

In this chapter a concrete complex regional situation is comprehensively analyzed and strategies to prioritize land-use optimizing economic and climate benefits are proposed taking local prevailing land-use, existing ecosystem C stocks, productivity and costs into account.

THREE.2 Material and methods

THREE.2.1 *Land management alternatives*

The study was performed in Thuringia, Germany, representing a region with typical geographic and economic features of central-western Europe. The relations between land-use, alternative management options and the flow of matter through product pools and reuse loops compared in this study are displayed in Figure 7.

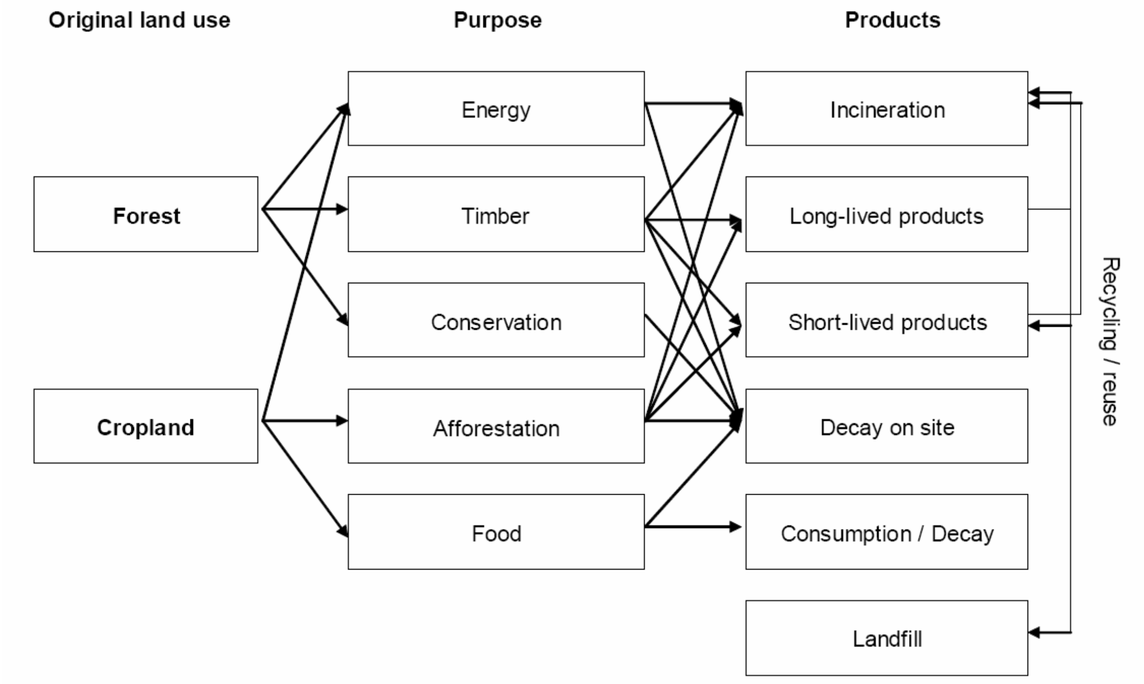


Figure 7: Relations between the land-use options, land management alternatives and the flow of matter through the product pools in the study.

In forests which cover 31% of area in Thuringia and are mostly constituted by Norway spruce (*Picea abies* L., 42% of forests) and European beech (*Fagus sylvatica* L., 20% of forests) following managements options are considered: a) timber production as reference, b) shift to shorter rotations for energy, and c) conservation for C sequestration. Forestry is bound to use indigenous tree species so that fast growing exotic tree species cannot be introduced at a large scale.

In croplands (38% of the area) the production of: (a) food cereals with straw remaining on site as reference (62% of cropland), (b) the use of straw for energy and (c) whole cereal crops for energy as well as (d) short rotation coppice of poplar for energy (clones of *Populus trichocarpa x Populus deltoides*), and (e) afforestation with slow growing oak (*Quercus robur L.*) for timber production, as example for a typical hardwood species suitable for these terrains were chosen to represent likely options on cropland. Deforestation is prohibited by law in the study region. The amount of extractable products and residues is restricted by the legal obligations to sustain forest productivity without fertilization and C stocks in cropland soils. Climate benefits and revenues were assessed per unit of land, the scarcest resource. For each management change, carbon stocks in ecosystems and products per hectare, their annual changes and the annual displacement of fossil carbon in energy and products per hectare, as well as annual costs and revenues were calculated. The land was stratified according to productivity, accessibility and current existing C stocks. Land management was modeled with the FORMICA model (Böttcher et al., in press). Data were taken from official Thuringian data sources and regional surveys. Assumptions and details are given in Table 5 and Table 6. Other parameters used in the model are listed in Appendix, Tables A1 - A4, A6 and A7. The forest area was stratified by productivity level and accessibility characterized by slope classes. The cropland conditions were relatively uniform and therefore not further disaggregated.

THREE.2.2 Dataset description

The original forestry model was extended to include carbon stocks and fluxes in cropland ecosystems and products. It was parameterized in the following way. The product module considered three product compartments for sawn-wood, pulp and bioenergy as well as partial recycling of sawn-wood and pulp for energy with species-specific mean residence times according to a Thuringian survey (Table 5; Mund et al., 2006).

Thuringian forests grow on relatively poor soils or on low mountain ranges with a wide range of environmental conditions: 28% of the forests have low, 36% medium, 36% high productivity represented by the site indices varying between 28 (low) and 36 (high). The site index refers to the average height in meters at age 100; 26% of forests have a flat slope (<15% inclination), 69% medium slope (15-24% inclination), and 5% a steep slope (>24% inclination). The two dominant forest tree species Norway spruce (*Picea abies L.*) and European beech (*Fagus sylvatica L.*) were studied. Forest management assumed regularly managed, regularly thinned, even-aged stands with relatively long rotations as typical for Thuringia. Growth was calculated according to regional yield tables for three site-dependent productivity levels with different yields and three slope classes affecting production costs.

Detailed thinning and harvest schemes derived from administrative recommendations and statistics for Thuringia were implemented fractionating products from thinning and harvest removals as pulp, sawn-wood, and energy. Fractionation parameters depended on forest age and species. A detailed description and references can be found in Table A3 in the Appendix that lists management related parameter values for different forest management options. Product decay rates were derived from a detailed regional survey (Mund et al., 2006). Due to the German ban of organic deposits in landfills, most of the pulp and sawn-wood is disposed of by waste incineration (UBA, 2005). A conservative recycling rate for energy of 80% was used here as reference case. The product pools follow respective decay functions (Table 5).

Table 5: Mean residence time (MRT) of the living biomass and product carbon pools in years. MRT of biomass pools was taken from regional studies. MRT of products was taken from (Mund et al., 2006). MRT of soil pools was estimated from own calculations with the YASSO module (Liski et al., 2005).

Species	MRT of living biomass C [years]				MRT of product C [years]			MRT of soil C [years]	
	Stem	Branch	Leave	Root	Sawn-wood	Pulp	Energy	Fraction	
Spruce	100	25	5	25	30	2	2	Soluble	2
Beech	150	33	1	33	25	2	2	Holocellulose	3
Wheat	-	-	1	1	-	-	2	Lignin-like	5
Poplar	5	5	1	25	-	2	2	Humus 1	21
Oak	200	50	1	50	40	2	2	Humus 2	208

Thuringian croplands are concentrated on richer soils and flat terrain with moderate water limitations in the lowland plains. Yields represented the Thuringian average over the last 20 years and mean values from regional bioenergy experiments. Initial C stocks in ecosystem, product and waste pools were determined by model spin-up to species and productivity specific equilibrium levels under reference management: Timber production in spruce and beech forests, and wheat use for food with straw remaining on site for cropland. Important management characteristics are given in Table 6. The economic scenarios included production costs for all forestry and agricultural management measures (forestry: planting, fencing, thinning, harvest; agriculture: tillage, seeding, fertilizer and pesticide applications, harvest, storage if applicable). Area-related costs (e.g. planting) were distinguished from yield related costs (e.g. harvest). Costs differed with forest age and topography but did not include any site specific variation in agriculture, where conditions were more uniform.

Revenues comprised wood sales and sales of cereal grains for food and agricultural products for biofuels. Prices for agricultural and forest commodities were derived from regional market surveys of 2005 (see Tables A6 and A7 in the Appendix). Additional region-specific subsidies for agricultural enterprises, energy crops, afforestation and non-use of mature forests were considered according to the legal situation in 2006 (TMLNU, 2004, , 2006).

Table 6: Characteristics of land management systems.

System	Main product	Rotation [years]
Spruce timber forestry	Timber (pre-commercial thinning: 0% sawn wood, 80% pulp, 20% energy; commercial thinning: 30% sawn wood, 50% pulp, 20% energy; final harvest: 80% sawn wood, 16% pulp, 4% energy; 80% of sawn wood and pulp recycled for energy)	100
Spruce energy forestry	100% of extracted wood for energy	60
Beech timber forestry	Timber (pre-commercial thinning: 0% sawn wood, 50% pulp, 50% energy; commercial thinning: 10% sawn wood, 30% pulp, 60% energy; final harvest: 55% sawn wood, 15% pulp, 30% energy; 80% of sawn wood and pulp recycled for energy)	150
Beech conservation forestry	None (C removal and storage)	None
Wheat cropland, food	Food grains, straw remains on site; grain:straw ratio = 1:1	1
Wheat cropland, food + straw energy	Food grains, straw for energy grain:straw ratio = 1:1	1
Wheat set-aside, energy	Whole plant for energy	1
Poplar set-aside, energy	100% of extracted wood for energy	3x5
Oak afforestation of set-aside cropland	Timber (pre-commercial thinning: 0% sawn wood, 80% pulp, 20% energy; commercial thinning: 30% sawn wood, 70% pulp, 0% energy; final harvest: 60% sawn wood, 40% pulp, 0% energy; 80% of sawn wood and pulp recycled for energy)	200

All model input, parameters and boundary conditions were based on detailed inventories and most recent statistical data from forestry and agricultural operations in Thuringia, Germany (Wirth et al., 2003; Mund et al., 2006). Thuringian official data sources were used for forest inventories, agricultural statistics, most recent cost structures of farms and forest enterprises and market prices for wood, agricultural products and biofuels, and subsidies (BMELV, 2006; TMLNU, 2004; TMLNU, 2005; TMLNU, 2006). The model was run at annual time steps per hectare. For comparability, all scenarios start at the beginning of a rotation at equilibrium conditions of the reference scenarios. The model was run over 300 years in order to provide at least two forest generations in the cases of management for wood products. Information about forest age-classes, topography and site productivity was only available at aggregated level so that no spatially explicit calculation of feasibility constraints was possible.

THREE.2.3 Fossil carbon displacement

The effectiveness of fossil fuel substitution by various biofuel types was calculated by life cycle analysis (Becher, 1998), and additional literature based assumptions (Kaltschmitt, 2001; LpB, 2001; TMWTA, 2005), focusing on stationary heat and electricity provision substitutable by solid bioenergy carriers (Equation 18). Data for substitution effectiveness *SE* were representative for Germany in the mid 1990s but are still valid today. Combinations of five biofuel types with six fossil fuels in specific conversion process types were considered which are representative for the situation in Germany.

$$SE = \frac{(FPE_{lc,\,ff} + FPE_{ff} - FPE_{lc,\,bf}) \times CER_{ff}}{BC} \tag{18}$$

, where

SE	Substitution effectiveness (tonne fossil fuel-C substituted per tonne of biofuel-C harvested)
$FPE_{lc,ff}$	Fossil primary energy use during the life cycle of the fossil fuel [GJ ha^{-1} yr^{-1}]
FPE_{ff}	Fossil primary energy stored in the fossil fuel [GJ ha^{-1} yr^{-1}]
$FPE_{lc,bf}$	Fossil primary energy use during the life cycle of the biogenic fuel [GJ ha^{-1} yr^{-1}]
CER_{ff}	Carbon emission rate of fossil fuel [t C GJ^{-1}]
BC	Biogenic carbon harvested [t C ha-1 yr^{-1}]

The regional substitution effectiveness *RSE* was defined as tonnes of avoidable fossil carbon emissions per tonne of biogenic carbon harvested. An adequate representation of the fossil fuel mix substituted is important because different calorific values and carbon contents have strong influence on the *RSE*. It is assumed that fossil fuels are substituted proportional to their share in the regional energy balance. The *RSE* was calculated by weighing the *SE*s in according to their contribution to the Thuringian primary energy balance of stationary fossil fuel use in the year 1999 (TMWTA, 2005, Equation 19). The resulting *RSE* was robust with regard to variations in the assumptions and life cycle emissions but very sensitive to the type of fossil fuel substituted (Table 7).

$$RSE_{bf} = \sum (SE_{bf,\,ff} \times w_{ff}) \qquad (19)$$

, where

RSEbf	Regional substitution effectiveness of a specific biofuel type
SEbf,ff	Substitution effectiveness of a specific biofuel – fossil fuel/conversion process combination
Wff	Weighting factor: relative share of the fossil fuel/conversion process combination in the Thuringian fossil fuel balance of 1999.

For comparison, Marland and Schlamadinger (1997) assume an *RSE* of 0.6 and Dornburg & Faaij (2005) an *RSE* of 0.3 in integrated gasification combined cycle systems against Western European electricity mix.

Table 7: Substitution effectiveness per fuel and conversion process combination, weighting factors reflecting the substitutable fossil fuel mix of Thuringia and regional substitution effectiveness for Thuringia (t fossil fuel-C substituted per t of biofuel-C harvested).

	Heat plant; natural gas	Combined heat and power plant; natural gas	Combined heat and power plant; light heating oil	Heat plant. Light heating oil	Power plant; hard coal	Power plant; lignite	Regional substitution effectiveness in Thuringia
Wheat, whole crop	0.36	0.38	0.53	0.54	0.70	0.75	0.49
Poplar, short rotation coppice	0.42	0.44	0.62	0.63	0.80	0.86	0.57
Spruce, wood for energy	0.42	0.44	0.62	0.63	0.81	0.87	0.57
Spruce, slash	0.44	0.45	0.64	0.65	0.83	0.89	0.59
Wheat, straw	0.45	0.47	0.66	0.67	0.86	0.92	0.61
Weighting factors	0.27	0.27	0.11	0.11	0.07	0.17	

Substitution of energy intensive materials such as steel and concrete in buildings by construction sawn-wood was calculated through special product substitution factors. Carbon displacement factors vary in a wide range depending on the substituted good, system boundaries, allocation of energy consumption between the by-products of the life cycles, and whether the waste wood is reused for energy after demolition of the building. We took the mean value and range of the studies reviewed in (Petersen and Solberg, 2005) that exclude reuse of waste wood in order to avoid double counting in our product cascade. Fossil C substitution can be particularly effective in high-yield systems. Substitution of pulp products by poplar from short rotation coppice is additionally considered in a sensitivity analysis. The C displacement factor here has a wide range, reflecting the wide range of possible pulp products (Dornburg and Faaij, 2005, Table 8).

Table 8: Substitution effectiveness of product substitution in addition to energy substitution. Data source: (1) Petersen and Solberg, 2005, (2) Dornburg and Faaij, 2005.

Wood product	Substituted material	Substitution effectiveness [t fossil fuel-C substituted per t of wood-C harvested]			Reference
		Value used in this study	Low range	High range	
Sawn-wood: spruce	Building Construction (concrete, steel, plaster)	0.24	0.046	0.56	(1)
Sawn-wood: beech	Building construction (concrete, steel, plaster)	0.16	0.029	0.36	(1)
Pulp from poplar	Boards, pallets and pulp (softwood), chemicals	0	0.19	1.46	(2)

THREE.2.4 Economic analyses

Economic instruments, like valuation of carbon through a tax, may be used to ensure that a certain amount of sustained changes in land management for carbon services are triggered at the level of individual enterprises and land holders. As the carbon balance varies among the management practices considered in this paper, the options were ranked in economic terms if carbon prices vary. In other terms, threshold levels for carbon prices might be identified above which it is economically sound to switch reference practices towards land management that maximizes climate change mitigation. The net carbon payment (subsidies when carbon accumulates, tax when carbon is released) necessary to trigger a certain carbon objective through management change is, per definition, the mitigation cost. This was analyzed by computing for each management alternative the net annual present value (NPV) per hectare at varying carbon prices. It was assumed that carbon payments are made annually. A carbon price of zero reflects the present situation. In practice, it is unlikely that all calculated climate benefits will be monetized as assumed here. Agriculture and some protected forests already receive other subsidies. Under the European Common Agricultural Policy croplands are eligible for general area-based subsidies and extra payments for energy crops (BMELV, 2006) of 45 € ha^{-1} yr^{-1} and of differentiated, site-, tree species- and measure-oriented payments for afforestation (TMLNU, 2006). Old trees and hardwood forests of high value for biodiversity can be subsidized if left unused by up to 120 € ha^{-1} yr^{-1} (TMLNU, 2006). NPVs were first calculated without such extra subsidies and then with all subsidies included. We determined, for time scales from a decade to centuries, the climate benefits of land management options in relation to different system boundaries: 1) the ecosystem perspective restricted to carbon stocks and their changes in the ecosystems, 2) the sector perspective including carbon stored in products, and 3) the comprehensive systems perspective including GHG emissions in the life cycles of products and services and the fossil C displacement by substitution of fossil energy in power plants and of fossil energy embedded in products. Economic analyses included varying discount rates and C prices as well as existing subsidies.

THREE.3 Results and Discussion

THREE.3.1 Carbon stocks at the ecosystem and sector level

Carbon uptake and storage by abandoned forest use (conservation) increased the long-term average C stocks in the ecosystems per hectare by about 70% as compared to managed beech forests (Table 9). Higher C stocks in the ecosystem under the conservation management more than compensated the substantial C losses in the product pool in which the historically accumulated wood products decayed (Figure 8).

Sustained high C input to the long-lived ecosystem pools of biomass and soil under the conservation management resulted in a net long-term average C gain in the forestry sector of about 50%. Energy forestry with spruce was set at intermediate rotation length that maximizes biomass yields. Although the average C stocks in the forest ecosystem in the energy option increased by 11% in comparison to timber forestry, the sectoral C stocks declined by 6% because the wood product pool was not replenished (Table 9, Figure 8).

Table 9: Long-term average C stocks of high (H), medium (M) and low (L) productivity. The allocation of C to the various product pools and assumptions about reuse and recycling are given in Table 5 and Table 6. *) mean residence time in product pools: sawn-wood = 25-40 years (species-specific), pulp and energy = 2 years, waste in landfills (historical pool plus 20% of wood product waste) = 200 years.

System	Average C stock in ecosystem			Average annual harvest			Average C stock in products *)			Average annual substitution in products			Average annual substitution in energy		
	[t C ha^{-1}]			[t C ha^{-1} yr^{-1}]			[t C ha^{-1}]			[t C ha^{-1} yr^{-1}]			[t C ha^{-1} yr^{-1}]		
	H	M	L	H	M	L	H	M	L	H	M	L	H	M	L
Forestry															
Spruce, timber	217	191	166	2.3	2	1.6	108	93	77	0.19	0.16	0.13	0.94	0.81	0.67
Spruce, energy	249	217	187	1.9	1.6	1.3	59	51	42	0	0	0	0.87	0.74	0.6
Beech, timber	232	216	200	1.9	1.8	1.6	50	46	43	0.04	0.04	0.04	0.88	0.82	0.76
Beech, conservation	399	372	345	0	0	0	28	26	24	0	0	0	0	0	0
Cropland															
Afforestation	158.5			1.09			27.9			0.04			0.48		
Poplar, energy	81.1			7.57			15			0			4.23		
Wheat, whole plant for energy	21.5			6.09			12.1			0			2.96		
Wheat, food grains + straw energy	21.5			6.09			12.1			0			1.84		
Wheat, food grains	42.2			3.04			6.1			0			0		

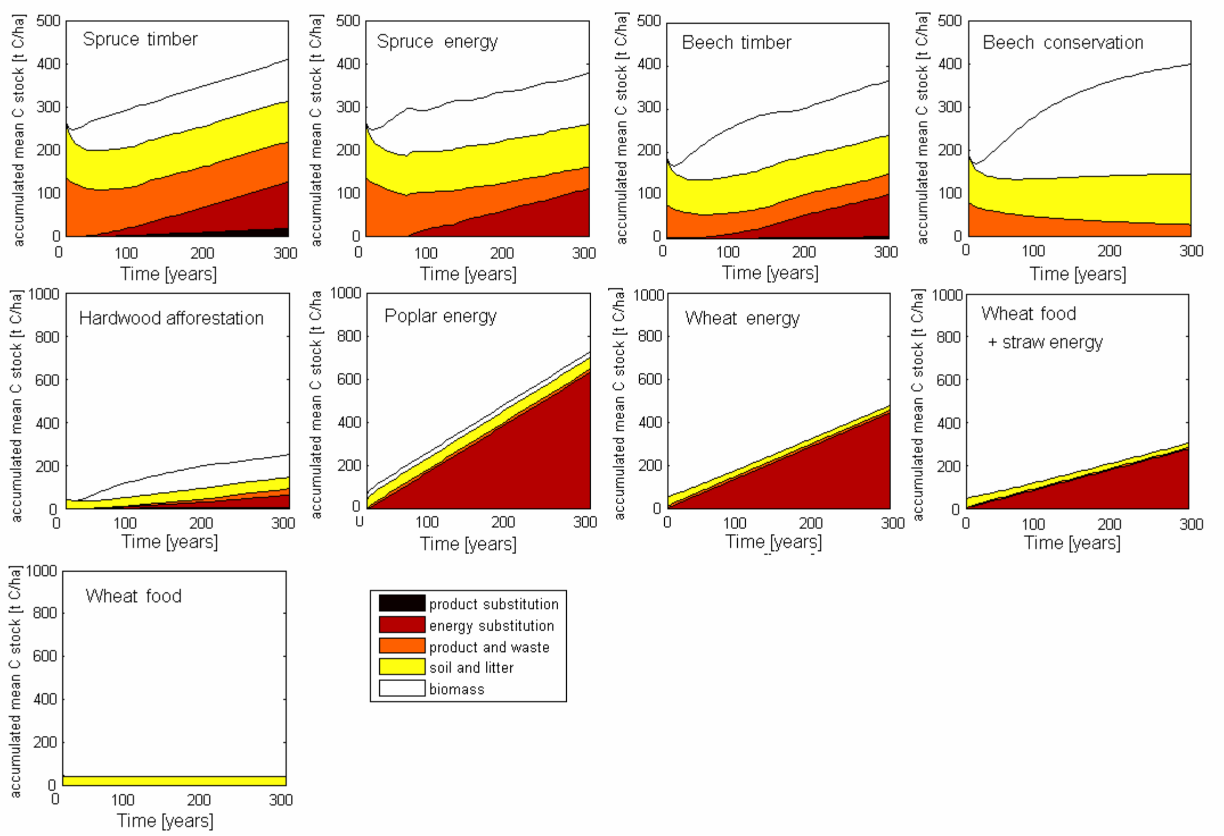


Figure 8: Development of carbon stocks in ecosystem and product pools plus substitution of energy and products in land-use options as accumulated mean over the simulation period. Forestry options refer to medium productivity. Agricultural sites are more productive than forest sites so that the forestry and agricultural options are not interchangeable. The scale of the y-axis differs between forestry and agricultural options.

Old waste wood in landfills with a long residence time usually constitutes a large fraction of the C stored in products (Table 5). Since 2005 Germany has banned by ordinance the deposit of organic materials in landfills (UBA, 2005) so that this pool is declining over time in the study region. Most of the existing product pool hence is historical (start value in Figure 8). Even in the timber option, the amount of C replenishing the product pool over the study period remained small due to the dominance of short-lived pulp products (Table 5, Table 6, Table 9, and Mund et al., 2006) and the almost complete incineration of wood waste in Germany (UBA, 2005). Considering C storage in the forestry sector (biomass, soil, products) without the substitution benefits makes conservation of forests most effective. At decadal time scales, the mean residence time of C in new products would need to be extended by 60 times in the case of beech to reach C storage levels equivalent to the conservation scenario.

As expected, agricultural lands had at least five to ten times lower C stocks than forests but were four times more productive. Removal of straw and harvest of whole crops for energy slightly depleted soil C while poplar coppice and afforestation increased the soil C pool as well as standing biomass (Table 9, Figure 8). Except for afforestation, due to high turnover rates, the agricultural management choices affected the C stocks in the ecosystem and the small product pools much less than forestry choices. Among the cropland options, despite intensive use, poplar built up the highest C stocks during the first 30 years until the hardwood afforestation took over (not shown).

THREE.3.2 Fossil C displacement

Carbon removal and storage in ecosystems tend to level off over time, whereas fossil fuel substitution can be endlessly repeated so that this indirect carbon service accumulates over time. The substitution of coal and lignite by bioenergy achieved the highest substitution effectiveness above 0.8 t fossil fuel-C substituted per tonne biofuel-C harvested, heating oil ranged around 0.6 and natural gas at 0.4. The regional substitution effectiveness (Table 7) was 0.5 t fossil fuel-C substituted per tonne biofuel-C harvested for whole cereals and 0.6 in the case of wood, wood product waste and straw. The difference reflects higher energy requirements and GHG emissions from fertilizer production and use in intensive annual crops. The regional energy system of Thuringia has been completely rebuilt during the past 15 years and is unlikely to change much during the next few decades. Over time, substitution effectiveness will decline as more efficient energy conversion processes will become available. This learning curve has not been considered here.

In our study, timber forestry was as effective in providing bioenergy as energy forestry because of efficient timber product recycling for energy. Thus, in a situation where wood waste incineration is used for energy provision, there is no climate argument for switching from timber production to energy forestry. In agriculture, the C stocks, high yields and high substitution effectiveness placed poplar as the best bioenergy option on a hectare basis. Over the whole period climate benefits from poplar were 50% higher than from energy cereals (Figure 8) because poplar had higher average yields and substitution effectiveness (Table 7 and Table 9). At all time horizons, C substitution in agriculture resulted in higher climate benefits than C sequestration by afforestation even in the option that only used straw residue for energy. The quantitative results of life cycle studies as presented here are sensitive to boundary conditions, assumptions and methodological issues and cannot easily be extrapolated to other regions. However, they give reliable relative indications of more or less effective choices (Farrell et al., 2006).

Wood products can also be viewed as substitute for energy intensive products. This second type of fossil energy substitution embedded in products has rarely been quantified by life cycle assessment (Dornburg and Faaij, 2005; Perez-Garcia et al., 2005; Petersen and Solberg, 2005) and so far been neglected in comparative studies of land-use options (Marland and Schlamadinger, 1997; Backeus et al., 2005; Perez-Garcia et al., 2005; Sohngen and Brown, 2006). Accounting for product substitution by sawn-wood (Table 8) increased climate benefits in the timber systems but the overall effect of product substitution was smaller than of energy substitution (Figure 8).

Reuse of products along recycling cascades adds another dimension of substitution, as recycling multiplies the services out of the limited biomass resource. Recycling is climate effective in most cases (Dornburg and Faaij, 2005). One intermediate product step can increase the annual CO_2 emission reduction per hectare of short-rotation coppice by a factor of three against immediate use for energy (Dornburg and Faaij, 2005) and benefits increase with yields (Marland and Schlamadinger, 1997). Consequently, in our case study, production of pulp from poplar tripled the substitution benefits compared to energy use (Table 9). In a comprehensive systems view, the production of renewable raw materials with subsequent reuse for energy turned out as most climate friendly on productive sites.

THREE.3.3 Total climate benefits

Total climate benefits were defined as the sum of C stocks and their changes in ecosystems and products and cumulative fossil C substitution. The cumulative climate benefit converged in the forest options over time while the agricultural options diverged (Figure 8, Table 9). The timing of switches between the most climate beneficial management depends on productivity and assumptions of forest growth. In the forest options all management scenarios started with the same C stock changes until the first thinning intervention necessary to produce high quality timber. This was usually at the age of 30 years (spruce) to 40 years (beech). From this time onwards, conservation forestry in beech forests turned out most beneficial for climate. Timber and energy forestry became as climate beneficial as conservation forestry after more than 250 years only. Even under very productive conditions the C losses induced by switching from long-rotation forestry to short rotation plantations would not be compensated within a century by fossil C substitution. There is hence no climate friendly alternative to maintaining forests with high average C stocks.

The situation in agriculture was much clearer. Considering C stocks only, poplar coppice scored best for the first 30 years until C stocks in hardwood afforestation started to exceed those in the other agricultural options. When the fossil C substitution effects were included, poplar coppice remained the most climate beneficial option.

Priorities for effective climate change mitigation can be derived from these findings. Forest management should strive for maintaining the high average C stocks by conservation (non-utilization) or maintained timber production with long rotations and wood recycling cascades for pulp and energy. In croplands where initial C stocks are low and productivity is high dedicated perennials and a fraction of the residues should be used for pulp and energy. This will require continued fertilization, associated with GHG emissions. The system effectiveness can be further enhanced by plant breeding and effective recycling along product chains and by local consumption.

THREE.3.4 Carbon prices and net revenues

Carbon price = zero

First, net revenues at a carbon price of zero were analyzed reflecting the present situation. The NPV is very sensitive to the period over which net revenues are cumulated and the discount factor used. As default, the NPV represented the cumulative net revenue over 300 years discounted by 1% annually. 300 years is the least common multiple of the forestry rotation options in the analysis. This long time scale represents equilibrium levels for average carbon stocks and climate services as well as revenues. The interpretation of the results is also valid for shorter decadal time scales. Positive discount rates act to scale down expected future revenues and costs, when balanced with present ones. Forestry lives on long-term investment. A sensitivity analysis showed that a discount factor of 5% was already too high to produce a profitable balance of forestry activities, characterized by early investments and operational costs and delayed harvest revenue obtained only at the end of the rotation period. At high discount rates, management that produce early revenue will be most competitive: conservation forestry if carbon is monetized (annual returns and no management costs), or agriculture (annual returns).

In forestry, any factor influencing the product prices and management costs (like slope conditions), or the obtained timber or carbon productivity (like species choice) will also strongly influence NPV. At a carbon price of zero and without subsidies, timber-oriented forestry turned out as economically preferred management on productive flat terrain and gentle slopes. On less productive and steep sites only conservation forestry produced a non-negative NPV (not shown). Low fuel wood prices against relatively high harvest costs (compare Tables A6 and A7 in the Appendix) turned energy forestry economically unfeasible under all forestry conditions, but fuel wood prices are rising quickly. Subsidies for mature beech forests of high relevance for biodiversity turned conservation into the most viable option. The subsidy is restricted to particular forest types and partly coincides with the areas of highest C stocks. On cropland, the highest farm income was achieved by production of food wheat combined with straw for energy since food prices exceeded energy prices. Area-based subsidies dramatically increased NPV of croplands but failed to make energy crops competitive with food production. Afforestation drastically reduced NPV by more than factor 10 to the level of forests because an afforestation premium was granted for the first 20 years only and agricultural subsidies ceased. The current subsidy structure discourages afforestation of productive land and fails to differentiate between the bioenergy options so that the most climate beneficial short rotation coppice is not yet pursued at large scale.

Carbon price > zero

Second, carbon prices for C sequestration and fossil C substitution were introduced in the analysis. If in the future every tonne of C sequestered or tonne of fossil C substituted was prized, the NPV of all options would increase (Figure 9, Figure 10). On productive terrain, the NPV of conservation, excluding subsidies, forestry with beech exceeded the one of timber oriented forestry at about 60 € t^{-1} C. This value is within the range of prices in the European CO_2 allowance market[2] of 35 to 70 € t^{-1} C in 2006. However, the threshold drops below the range (15 € t^{-1} C) if subsidies are included. Energy forestry remained uncompetitive under Thuringian land management constraints.

In croplands, C prices above 60 € t^{-1} C favored pure production of energy over food production (Figure 10). Afforestation of cropland with slow-growing hardwood remained uncompetitive even at very high C prices for C sequestration. The current and expected further rise in energy prices is likely to increase returns from bioenergy options. But C stored in ecosystems risks to be lost by disturbance or management choices. This

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[2] see: http://www.climatecorp.com

dichotomy could create a situation in which market prices for fossil C substitution exceed those for C sequestration in ecosystems.

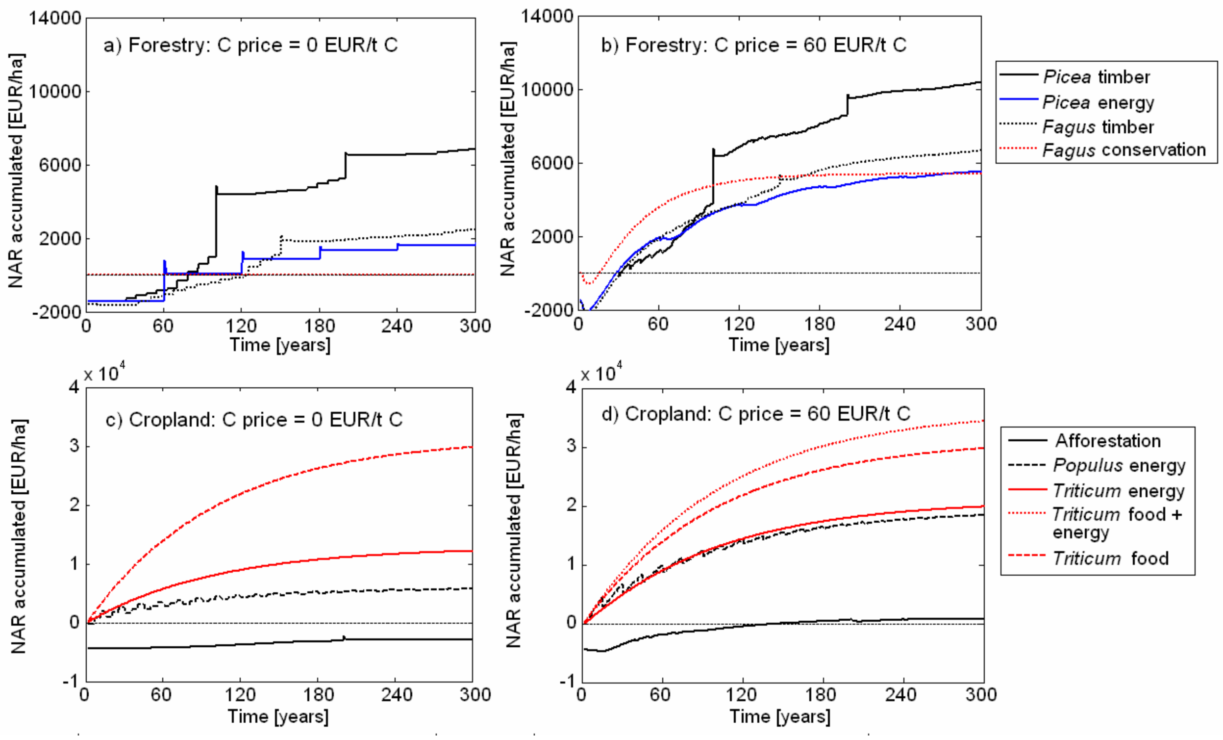


Figure 9: Cumulative net annual revenue (NAR) of forestry (top: a, b) and cropland options (bottom: c, d) calculated with a discount factor of 1%, medium forest productivity, no subsidies and a C price for removal and storage and substitution of 0 Euro t^{-1} C (left: a, c) and 60 Euro t^{-1} C (right: b, d). The values given at time = 300 years indicate the net present value (NPV).

Forestry options were most influenced by the valuation of their C stocks and C sequestration. Higher prices for fossil C substitution for wood energy products would still not make energy forestry profitable. Agricultural options were most influenced by fossil C substitution prices. The current agricultural area-based subsidies, independent of production and potential C prices, do not favor the most climate effective bioenergy production on a per-hectare basis. Only C prices oriented at the fossil C substitution effectiveness such as in this study create incentives to produce bioenergy from short rotation coppice or other perennial crops with slightly higher production costs and significant social barriers for adoption in practice. Such schemes will also help to maximize energy production from other effective sources of residues and waste. The average regional substitution effectiveness introduced in this paper could guide regional incentive structures. Use of the raw materials prior to energy conversion needs to be emphasized in order to maximize the per-hectare climate benefits and to reduce pressure on productive land.

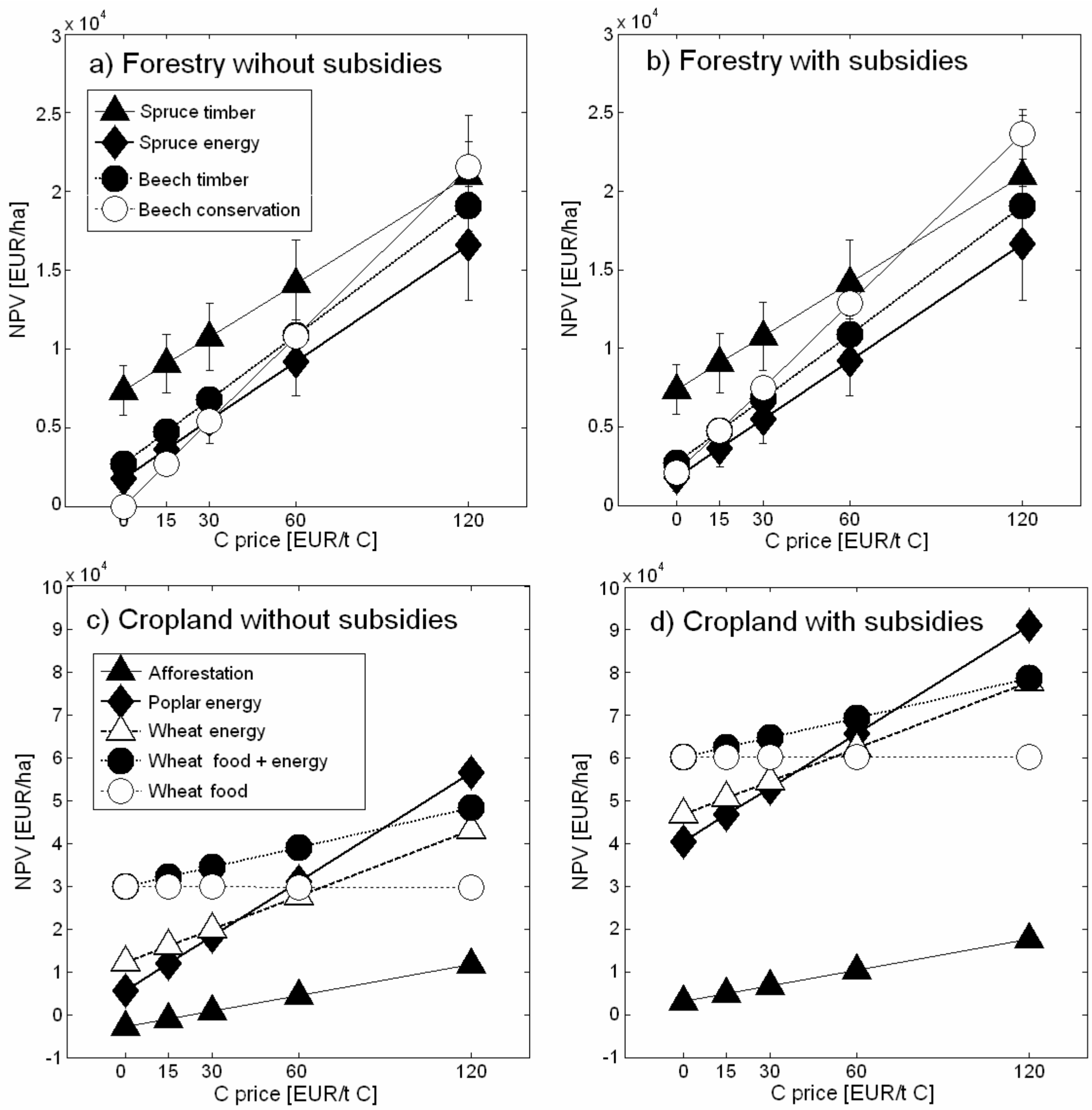


Figure 10: Net present value (NPV) of land management options in forest (upper figures a) and b)) and cropland (lower figures c) and d)), without subsidies (left a) and c)) and with subsidies (right b) and d)) with changing price for carbon (both sequestration and substitution). Forestry options refer to medium productivity. Error bars in a) and b) show variation between high and low site productivity, symbols medium productivity.

The optimal land-use role in climate change mitigation depends on regional existing C stocks, risks of losing carbon by disturbance and land-use change, production costs and market values for energy and products. In Thuringia, forestry would still optimally focus on C timber production on accessible terrain and shift to conservation on steep slopes while agriculture would expand its role in bioenergy production on land that is currently not needed for food production. Generalizing the per-hectare results, this study demonstrates that a region with diverse production conditions (present land-use, C stocks in ecosystem pools, productivity, accessibility, costs, subsidies, production goals) offers different niches for land holders for land management that serves climate change mitigation and economic purposes. Climate and economic benefits by C sequestration and substitution can be added to the traditional production of high-value products if moderate C prices at the level of opportunity costs and efficient product recycling are introduced.

THREE.3.5 Implementation

In Thuringia, a strong pressure on traditional long-rotation forestry towards shorter rotations for spruce comes from growing demand for small diameter timber for modern products, such as compound wood, and rising prices for fuel wood (the latter affecting all species). The age-class distribution of Thuringian forests is unbalanced (Wirth et al., 2003). Spruce forests are dominated by young stands with moderate C stocks so that there is some flexibility with regard to the harvest age without affecting the present total regional C stocks. In contrast, old beech forests of high biological value and high C stocks are common. Shorter beech rotations would reduce total regional C stocks (e.g. also Sohngen and Brown, 2006). Subsidies of 120 € ha^{-1} $yr^{-1}$are already in place for maintaining long rotations in protected beech forests but will need to be expanded or amended by C credits to a wider range of hardwood forests in order to conserve the existing large total C stocks in Thuringian forests.

Carbon services add a new demand on productive land, which is competing with the demands for food, fiber, wood and energy. Shifting land production goals from traditional goods to energy or conservation of C stocks may trigger declining C stocks, higher emissions and other environmental trade-offs elsewhere to compensate for the production losses and to satisfy human needs (Mayer et al., 2005). The high intensity of production in industrialized countries leaves little scope for further intensification or extension of productive areas without negative impacts on biodiversity, additional pollution or other negative side-effects although a segregation between intensively used productive land and unproductive land for C storage and biodiversity purposes was proposed (Huston and Marland, 2003; West and Marland, 2003). Figure 11 instead describes a gradual system along a matrix that prioritizes climate friendly land-use options by criteria of currently existing C stocks on land, productivity and accessibility. When quantitatively scaled to the region of interest (local to global) it could serve as a tool for land-use planning. Climate friendly land-use would maintain the existing carbon stocks and productivity of the land.

The recycling of products still offers significant easy-to-mobilize short-term potential for meeting demands for fiber, wood and energy. As demonstrated in this case study, an efficient recycling of timber for energy almost doubles the amount of useful products per hectare of land as compared to waste disposal. More elaborate recycling cascades through various steps of wood and fiber reuse can magnify the amount of goods and services derived annually from each hectare of land without increasing land-use intensity.

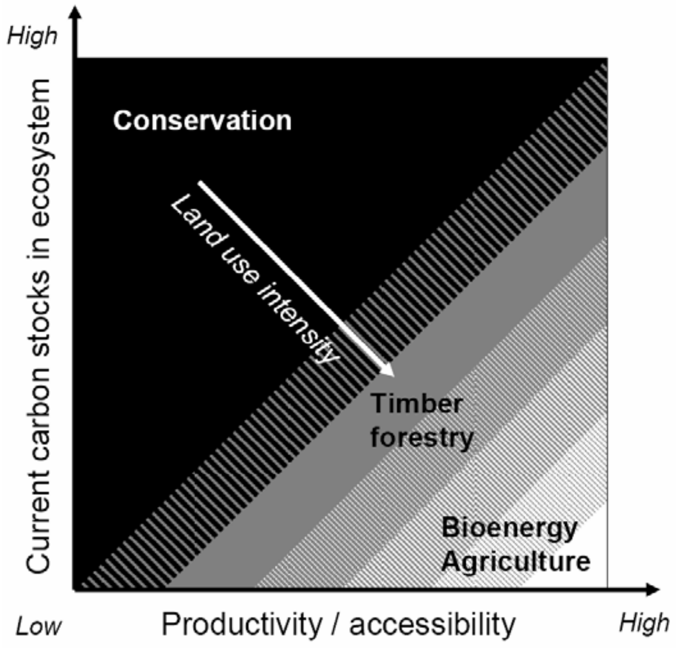


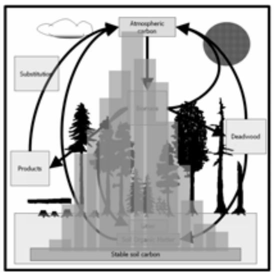
Figure 11: Matrix guiding land management decisions for effective climate change mitigation. Black = conservation, grey = forestry, white = agriculture.

THREE.4 Conclusions

The perspective on climate benefits matters. An ecosystem- and sector-centered view favors the conservation of forests and afforestation while a holistic systems perspective highlights additional opportunities in long-rotation timber production and in particular for bioenergy production in agriculture. In Central Western Europe, forestry is dominated by the production of high-value timber while many forests with low productivity and on steep slopes have already slipped out of use. The most striking finding of this case study is that the economic conditions in Central Western Europe have already created an almost optimum climate benefit from forestry, where energy recycling of wood products is intense. Overcoming the relatively small economic barriers for adopting the production of raw materials and biofuels in agriculture can greatly increase the climate benefits. The presence of C stored in ecosystems and products has so far been neglected as value in the context of climate change. Precautionary measures would subsidize land-use systems that maintain high average C stocks in the long term, such as long-rotation forestry and conservation, which may otherwise risk to be lost by short-term economic considerations and other land pressures. Only effective recycling frees land for long-term sustained C sequestration by conservation, or alternative non-marketable uses, beyond the present state without additional emissions from shifting production or intensification. Innovation in reuse of forestry and agricultural products can also create new job opportunities in rural areas.

FOUR

SENSITIVITY AND UNCERTAINTY ANALYSIS OF THE FORMICA FORESTRY MODEL



FOUR.1 Introduction

Model parameters and model inputs are not constant values. They might vary with environmental conditions, geographical locations and time. In addition, there is also an intrinsic uncertainty associated with them. The source of uncertainty is manifold: e.g. a known error of the measurements applied to obtain the value, a product of the integration over different processes etc. In the following it is investigated a) how changes in parameters and initial conditions influence model output, b) how uncertainty of parameters and initial values is propagated through the model, and c) how uncertainty affects the capacity to model quantitative effects of management changes on C stocks and fluxes.

Models describe systems that are characterized by interaction between system components. Sensitivity analysis in general is a tool that assesses the significance of these complex interactions within a system (Brylinsky, 1972). By changing values of one or more system parameters the response of the system as a whole is altered and the amount and direction of system change produced by a certain parameter change is determined. This reveals how system parameters and compartments are interlinked and dependent on each other and how much the uncertainty in one parameter determines the uncertainty of the overall results.

Sensitivity analysis has become a popular tool also in forest ecosystem and forestry modeling research (e.g. Battaglia and Sands, 1998; Esprey et al., 2004; Brainard et al., 2006; de Wit et al., 2006; Tatarinov and Cienciala, 2006). The purpose of this chapter is a sensitivity analysis of the forestry model FORMICA presented in Chapter Two to explore the dependence of processes represented in the model and model output with respect to selected input parameters.

Because any parameter could be changed in various ways and the effects on any other parameter could be examined, the number of sensitivities that can be determined is enormous. The analysis has to be limited to key parameters and has to be organized in an efficient way. This sensitivity analysis explores carbon stocks and changes in biomass (above- and below-ground), on forest ecosystem level (including soil and litter C), on the level of the forestry sector (considering C in harvested wood products) and in a comprehensive systems perspective (including the yield of fossil fuel substitution through energy and product substitution). The dynamics of these different perspectives depend to a large degree on forest growth, management intensity, product allocation, product lifetimes etc. To focus the study and the interpretation of results, the set of parameters closely related to these processes was included in the analysis. Among these parameters absolute and relative sensitivity of the model reaction to parameter changes were looked at. The results are used to point out parameters and processes that influence model output most. This knowledge is not only helpful for the interpretation of model results but can contribute also to an evaluation of the uncertainty of model results with respect to uncertainty in parameters and other input data, which is done at the end of the chapter. Real data of the forestry sector of Thuringia, reflecting conditions of Central Europe, is then used in a regional study to highlight effects of uncertainty propagation through the model and point out implications for the different levels of perspective on system boundaries.

FOUR.2 Methods and material

FOUR.2.1 Calculation of sensitivity indices

The amount of change produced in one system variable X divided by the change in the input parameter p describes the absolute sensitivity λ_{abs} as rate and direction (see Equation 20). The direction can either be positive or negative, depending on whether an increase in p results in an increase or decrease in X. A value of zero would mean that X is independent from p.

$$\lambda_{abs}(X, p) = \frac{\Delta X}{\Delta p} \tag{20}$$

For a comparison of the sensitivity of various parameters the rate can be set into relation to the initial values of both parameters p and X, resulting in the relative sensitivity λ_{rel} (see Equation 21, Brylinsky, 1972).

$$\lambda_{rel}(X, p) = \left(\frac{\Delta X}{\Delta p}\right) \times \left(\frac{p}{X}\right) \tag{21}$$

If the value of relative sensitivity is one, this indicates that a percentage change in the value of a parameter p will result in the same percentage change in the variable X. Relative sensitivity was calculated for the results of three model runs for each parameter and averaged.

The general procedure for the sensitivity analysis was the following: one set of model runs for each parameter was performed. The set comprised $n=7$ model runs per parameter. The runs sampled parameter values p with a range r starting from the lowest value $p-r/2$ and sampling further with a step of r/n to the highest value $p+r/2$. This sampling changes the parameter value gradually with a constant step size. The number of samples n was set to seven to have enough sample points to assess non-linearity with changing parameter value. One reference run was performed where all parameters were kept fixed and no variation at all was allowed.

FOUR.2.2 Hierarchical clustering of parameter sensitivity

Klepper (1997) used hierarchical clustering to highlight similarly behaving groups of parameters in a dendrogram. This approach was applied to the results of the FORMICA parameter sensitivity analysis. A dendrogram of the cluster can be drawn in the following way: First, the Euclidean distance between pairs of relative sensitivity values were computed. Then, the obtained matrix was clustered by complete-linkage clustering, in which the distance between one cluster and another cluster was considered to be equal to the greatest distance from any member of one cluster to any member of the other cluster.

FOUR.2.3 Model variables included in analysis

FORMICA supplies some dozens of output variables that can be read out and investigated. To limit the number of sensitivities and focus the analysis, this study included only some output variables and their derivatives. The most important output variable delivered by FORMICA is the sum of C pools on different levels of aggregation, which are: a) the biomass perspective, b) the forest ecosystem perspective as the sum of biomass, soil and litter, c) the level of the forestry sector, and finally d) a sum of all pools including C from fossil fuel substituted through wood products and energy production from biomass (the comprehensive system perspective). The development at the systems perspective projected by the model is of highest relevance in terms of climate change mitigation (see Chapter Three). A change of any parameter should have an effect on the comprehensive level of aggregation. Otherwise the parameter can be considered irrelevant. There are parameters that are by definition of the system excluded from certain pools or processes (e.g. substitution effects in a conservation scenario). However, it makes sense to also look at the contributing pools separately (biomass, ecosystem, forestry sector and substitution C).

Forest management is characterized by discontinuous single events as well as by parameters that have a continuous influence. These events affect pools in different ways and often with a different signature. Due to different parameters controlling the pools, uncertainty among them differs. This has to be taken into account when integrating over these pools. To make sensitivities more comparable among parameters, time was not considered as a factor in this analysis. C pools and their change were averaged over the respective simulation period.

FOUR.2.4 Forestry model parameters

The analysis covers parameters of thinning intensity, rotation length, wood density, biomass turnover rates, product allocation, and substitution factors. Altogether 19 parameters considered in FORMICA were included in the analysis. Table 10 and the following section give the definition and standard operating value of these parameters.

Wood density

A potentially high influential factor is wood density or the dry weight per unit volume of wood, which converts stem volume to biomass. Wood density varies with tree species, growth conditions and part of the tree measured. The main stem generally has a higher wood density than the branches, while fast growth is generally related to relatively low wood density. For most species the literature gives a range with low, medium and high values (e.g. Joosten et al., 2004; Cienciala et al., 2005). It is thus a relatively well described parameter with a known uncertainty. In this study the parameter was constrained to vary within a standard deviation of 10%.

Uncertainty about natural mortality and maximum biomass

When assessing the forest C budget knowledge of biomass growth and natural mortality is needed. Biomass is often the largest C pool in many forest ecosystems and therefore the most relevant contributor to total forestry and substitution C. Representation of C flux due to forest growth and mortality in the FORMICA model is simplistic compared to the underlying biophysical processes. A sensitivity analysis can help to examine some of the uncertainty related to growth and natural mortality and also effects of environmental change on it, which are not captured by the model approach.

Table 10: Parameter description and assumed coefficient of variation (CV). Mean values for the parameters are given in Tables A2 and A2. References: (1) Wirth et al., 2003, (2) Joosten and Schulte, 2002, (3) Muukkonen and Lehtonen, 2004 , (4) Mund, 2004, (5) Freibauer et al., submitted, (6) for roots we assumed the same uncertainty as for branches due to lack of data, (7) spruce, Assmann, 1961; others estimated from yield tables, (8) respective yield tables: spruce, Assmann, 1963; pine, Lembcke et al., 1975; beech, Dittmar et al., 1983; oak, Erteld, 1961, (9) Wutzler, personal communication, (10) Mund et al., 2006, (11) Profft personal communication, (12) expert guess, conservative.

Group	Parameter	CV [%]	Reference
Biomass	Wood density	8	(1,2)
	Biomass turnover foliage	15	(3)
	Biomass turnover branches	70	(4,5)
	Biomass turnover roots	70	(6)
	Max volume	20	(7)
Management	Removed fraction of stem by thinning	20	(8)
	Rotation length	30	(9)
	Fraction of harvested stem to sawn-wood	10	(10)
	Fraction of harvested stem to pulp wood	10	(10)
	Fraction of harvested stem to energy wood	10	(10)
Products	MRT sawn-wood	10	(11)
	MRT pulp wood	10	(11)
	MRT energy wood	10	(11)
	Fraction to energy from sawn-wood	20	(12)
	Fraction to energy from pulp wood	20	(12)
Substitution	Product substitution factor	40	(5)
	Energy substitution factor	18	(5)
Start values	Start value for soil and litter C pool	10	(1)
	Start value for product C pool	10	(10)

Biomass compartment turnover in FORMICA refers to the percent of the respective C pool replaced every year. In the analysis, the factors were set not to exceed 1.0 and kept fixed to 1.0 for foliage of beech. Besides foliage turnover root and branch turnover were changed within a standard deviation of 10%. Whole plant mortality in FORMICA is controlled by maximum volume, marking the point at which losses through autotrophic respiration equal the gain through NPP. Maximum volume is a crucial factor that is influencing biomass C stocks and that is varying over species, site and climate conditions. Compared to turnover, maximum volume is relatively more uncertain due to site conditions and disturbances. It was considered to vary within a standard deviation of 20%.

Rotation length and thinning intensity

The longer a tree stands, the more C it accrues into biomass, and the later the C in its products will be released to the atmosphere. However, the rate of C uptake depends on tree age, with trees that are past their growth peak tending to take up C very slowly. The harvest age of trees is therefore important. According to tree growth but also to the applied management, the wood product aimed at and economic conditions, the length of rotation in the real world might vary tremendously. The sensitivity of model results to such a varying rotation length is tested within a standard deviation of 10%.

Besides harvest age, thinning influences biomass, litter and soil and potentially product C stocks. The number of thinning events, the intensity of each event and the allocation to wood products (or slash in the case of pre-commercial thinning) play a role. This study focused on thinning intensity by varying (stdev. = 20%) the amount removed from standing volume at a thinning event.

Product allocation and mean residence time of product pools

C release from harvested wood products in the FORMICA model follows general decay functions (see Chapter Two). The model assumes for Thuringian conditions that on average 75% of stem biomass of mature trees ends up as merchantable products. The C in the other remaining fraction (roots, needles, etc.) is assumed to gradually decay into the atmosphere or contribute to long-term storage in soil pools. The allocation of the extracted C to product pools differs among tree species and with timber dimension. A change in the allocation pattern has a similar impact on related output variables like changes in mean residence time of certain product pools have. Both parameter groups were included in the analysis with a standard deviation of 10%.

Substituted C in harvested wood products

Wood products can substitute for other materials that require more energy to be produced and processed, such as plastic, steel or aluminum. The amount of C displaced varies by type of wood product, regarding the energy uptake for manufacture and variation in product lifetimes depending on the material. The properties of these processes can be summarized in a product specific substitution factor (see Chapter Three). However, the aggregated substitution factor accumulates also the uncertainty related to the processes considered. A sensitivity analysis offers the opportunity to test alternative displacement factors for harvested wood products and analyze implications for total C substituted. For conditions in Thuringia the uncertainty of this parameter can be constrained with data from life cycle analyses. The uncertainty, however, is high (stdev. = 40%).

Initial values for soil and product pools

The initial values in model simulations are crucial and can have a large influence on model results, especially stock and stock change development over time. This is due to the fact that if the initial values disagree with the model equilibrium state at which import and export of material balance, the model variables converge to this equilibrium. This creates stock changes that emerge merely from the initial imbalance and not a change in parameters. Initial values are therefore often derived from a spin-up model run that fills up stocks until long-term pools reach their equilibrium. The initialization of the product and soil and litter pools in FORMICA is done through a similar spin-up run setting all compartments to steady state, for each stratum separately. This is on the one hand a prerequisite for the soil model application and makes it possible to study effects of parameter change on certain pools without results biased by inappropriate starting conditions. On the other hand this is done because there is often a lack of empirical data to estimate these pools' initial state. In this sensitivity analysis it was tested how uncertainty in the initial values for soil, litter and product pools affect model results (stdev. = 10%). In the uncertainty analysis initial volume is also considered to have an uncertainty of that magnitude. It can be considered a typical value for the uncertainty of larger forest inventories.

FOUR.2.5 Model runs for sensitivity analysis

FORMICA was applied on the plot level to five forest management options, namely options for timber production and C conservation (no wood extraction) for beech and spruce and another option where spruce is grown for biomass production for bioenergy. The runs are performed on plot level to exclude the impact of area share and shifting. Table 6 in Chapter Three lists the considered options (forestry only) and gives details. The simulation time for all options is 300 years to allow for full rotation sequences. The simulation runs consider a pre-run that initializes soil and product pools for each option. Biomass pools, however, start at low initial values, imitating regeneration after biomass removal. Annual increment in stem volume, turnover of roots and leaves, management rules as well as parameters for decomposition of biomass as litter refer to average values for species growing in Thuringia (see Appendix, Table A1).

FOUR.2.6 Uncertainty analysis

The study of uncertainties uses data of the Thuringian forestry sector. The assessment was done by including variation of all parameters used in the sensitivity analysis in a single set of Monte Carlo simulation runs. All parameters were considered to follow a Normal distribution in their natural uncertainty (see Table 10) from which they were randomly sampled. The number of runs was set to 500. This number turned out to be sufficient to represent the distribution and yet not to exceed computation time and software memory too dramatically. The model simulation period was 60 years. This period is probably too long for an appropriate uncertainty assessment at the end of the period but it is a reasonable period of time to evaluate the projected future development of the forestry sector and impact of management change.

Model initialization

The study area amounts 415 600 ha of forest land. Four species are taken into account, Norway spruce (*Picea abies*), European beech (*Fagus sylvatica*), Scots pine (*Pinus sylvestris*) and oak (representing two similar species: *Quercus petraea and robur*), in the following referred to as spruce, beech, pine and oak. Norway spruce and beech together cover nearly 75% of the forest area in Thuringia (Wirth et al., 2003). Growth parameters for each species and three site classes each were derived from Thuringian and Bavarian yield tables (spruce from Assmann, 1963; Pinus from Lembcke et al., 1975; beech from Dittmar et al., 1983; oak from Erteld, 1961).

The age-class distribution is typical for German forests: there is a high proportion of middle aged coniferous forests due to intensive cuttings after World War II and a relatively large portion of old broadleaved forests (Figure 12).

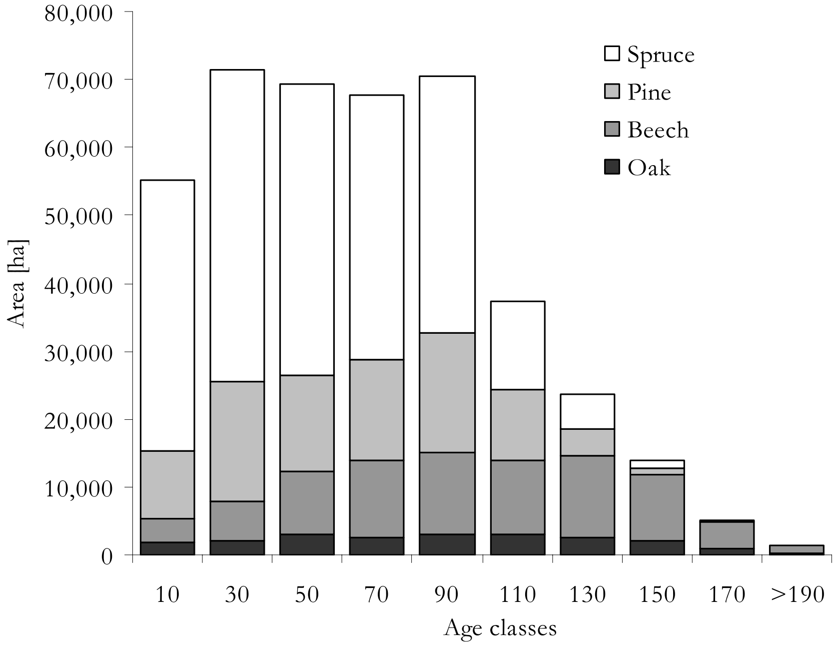


Figure 12: Age-class distribution of the four considered species in Thuringia (Wirth et al., 2003). X-axis shows mid point of age-classes that are 20 years wide.

The inventory reference year is 1993. Start values per age-class and species, parameters and coefficients for different species are listed in Appendix, Tables A1, A2, A3 and A6. Soil model and product model were initialized with values for each species, management type and age-class obtained from a 3000 year spin-up run keeping management, mortality and litter parameters constant. The spin-up run results in a state that is close to equilibrium where soil and product pools with long mean residence times stabilize. By using these values as start conditions the impact of changes in forest management on soil C can be assessed. However, Thuringian forest soils have experienced disturbances in the past and are thus very likely not in an equilibrium state. We will thus only focus on effects differing from a baseline.

Scenario description

Typical features of the silvicultural systems applied in Thuringia are relative long rotation periods with 100 years for spruce, 110 years for pine, 150 for beech, and 200 years for oak stands. Rotation length is generally determined by tree dimension rather than stand age. Average rotation length were derived from an analysis of one representative forestry district situated in eastern Thuringia except for oak (Wutzler, T., personal communication). For oak general recommendations on rotation length were used. A more detailed description of the management can be found in Appendix, Table A3. The area to be harvested each period is restricted to Normal Forest area to allow continuous timber flow. In a baseline scenario this management is applied to all Thuringian stands and considered as Business as Usual.

Table 11: Scenarios applied on Thuringian test case.

Scenario	Description
Business as Usual	Continued classical management; regular thinning, clear-cut, rotation forestry applied to all species
Longer rotation	Increased rotation length of all species
Shorter rotation	Decreased rotation length of all species
Species change	Species change from coniferous (pine and spruce) to broadleaved (beech and oak), system change with overlap at the end of coniferous rotation, new beech stands managed classically according to Business as Usual
Conversion	Change in management from rotation forestry to continuous cover forestry, applied only to spruce and beech due to physiological reasons
Conservation	Conservation of oldest forest stands, all species

The future development of forest management in Thuringia (as elsewhere) is uncertain and depends on external variables, such as market conditions, forestry policy etc. Therefore, besides Business as Usual five management change scenarios were simulated: Longer rotation, shorter rotation, species change, conversion and conservation (Table 11).

The scenario of longer rotations is considered a measure that could lead to an increase in forest biomass and remove CO_2 from the atmosphere additionally compared to Business as Usual temporarily by delaying harvest and likely leading to higher average C stocks. In this scenario a general prolongation of rotations by 20% for all species is prescribed. But there is also a trend towards compound products, resulting in a higher demand for sawn timber of smaller diameters. It is likely that economic conditions will favor a reduction of rotation time in the future in some forest management regions. A scenario of 20% shorter rotations in all forest regions is estimating implications for the carbon budget if the average forest age would be reduced.

Species change considers a switch from the current distribution of 33% broadleaved to a higher share of broadleaved trees, a declared aim of the Thuringian forestry administration for the next 50 years. In the case of a switch from spruce to beech, trees are usually planted under the still existing cover of spruce trees. We account for the overlapping of the two systems by applying preparation cutting. The resulting increase in biomass is then considered to refer to young beech in the understorey. In the final cut only 80% of the biomass is removed, 20% is left as beech regeneration. The newly established beech and oak stands are managed according to the Business as Usual rules. The conversion scenario simulates a management change to continuous cover forestry for beech and spruce stands. Conversion is limited to beech and spruce because of their physiology (shade tolerance). The main difference to the Business as Usual scenario is a continuous intensive thinning instead of final harvest. An additional scenario is conservation. Conservation means that forest area is taken out of wood production and neither thinning nor harvest is applied anymore.

The level of implementation of management change was represented in two versions of each management change option. In a low level implementation simulation the target area of management change scenarios was set to 20% of the respective forest area. A management change introduced on 20% of the area can be considered a feasible target over a period of 50 years and is in fact in line with targets forestry authorities aim at in reality. The high level implementation simulation, as an extreme variation, introduces management change on 100% of the respective area. We assume that management change is only possible at the end of a rotation. The rate of change, and thus the time it will take to achieve this goal, depends on the age structure of the forest. The onset of management change was set to the year 2007.

FOUR.3 Results and discussion

FOUR.3.1 Model sensitivity on plot level

Figure 13 lists the produced range in average change in C in forestry sector and substitution for the five forestry options, sorted after its magnitude. Rotation length and energy substitution factor turn out to have the largest absolute influence for options considering harvest. Changes in the maximum volume parameter have largest effects on both conservation options. Wood density shows a high absolute sensitivity for all options. Sensitivity is zero for those parameters and for those options where the processes controlled by the parameters don't play a role (e.g. substitution in conservation options).

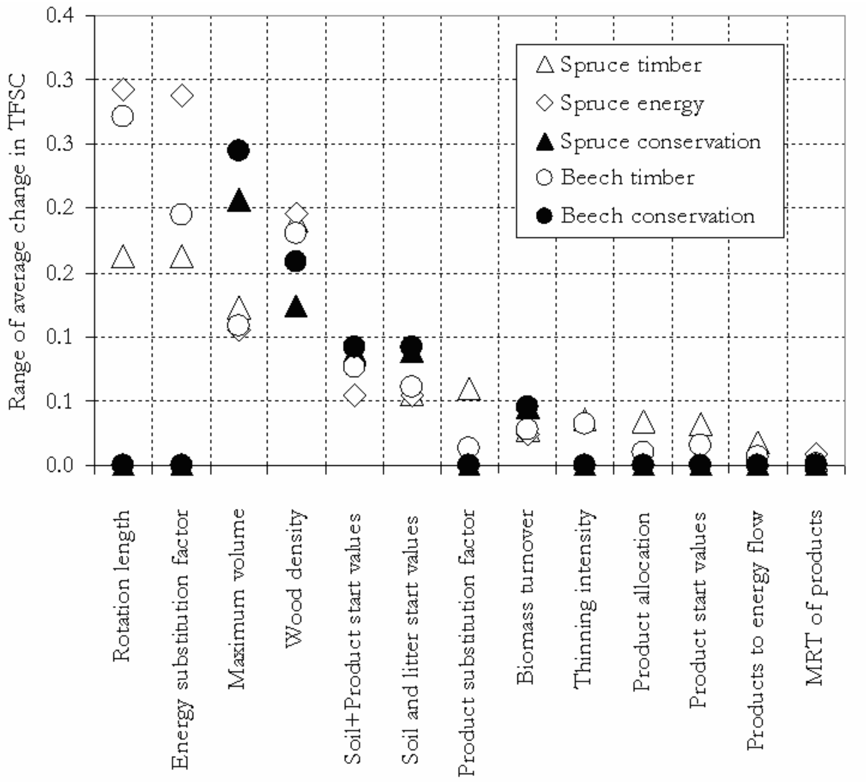


Figure 13: Sorted range of average change in total forestry sector and substitution C (TFSC) associated with change in respective parameter values. Sorting criterion was the magnitude of largest range among the five forestry options. 'Range' is here the absolute range of the model variable, the difference between minimum and maximum.

Figure 14 shows the range of average TFSC as a function of absolute change in parameter. The graphs allow a direct visual examination and illustrate the various degrees of sensitivity found in the model. In general, if the plot of output *X* versus parameter *p* is not a straight line, then *X* is nonlinearly related to *p*.

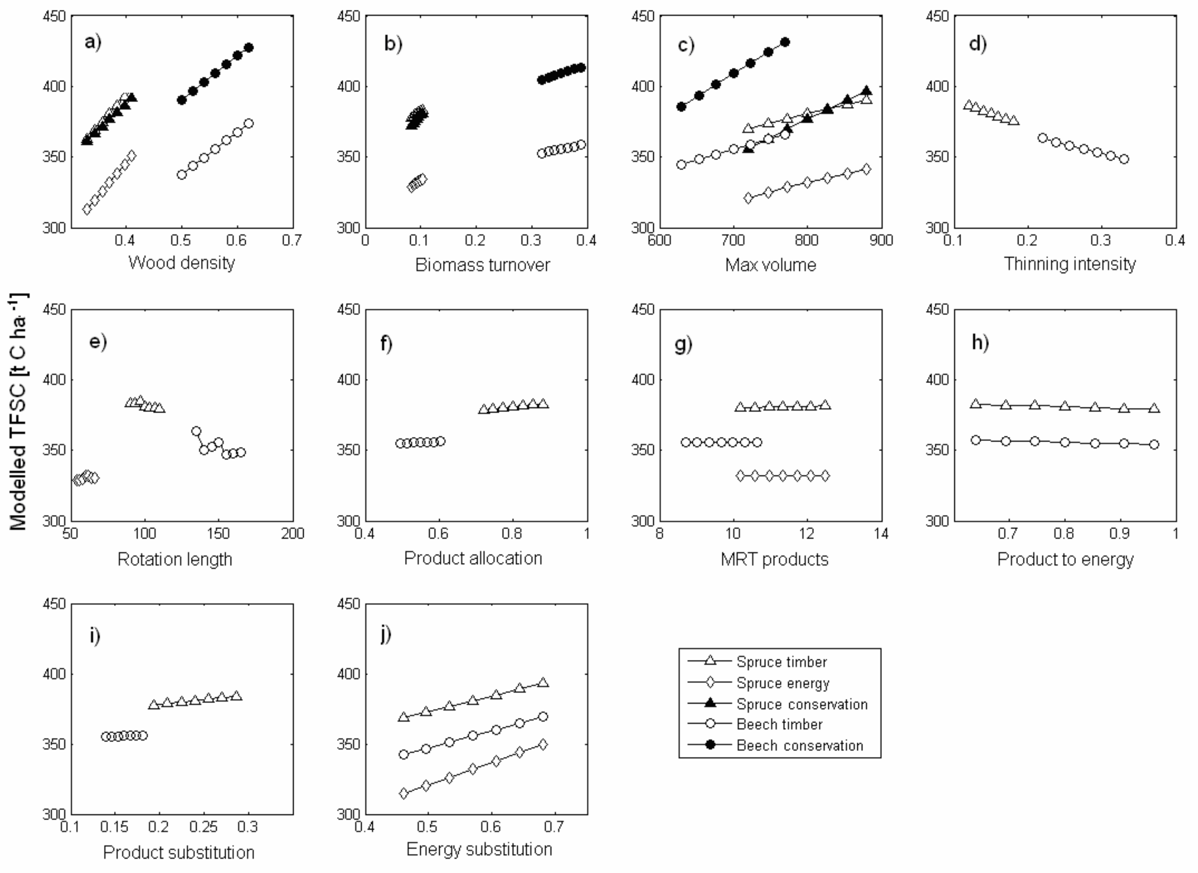


Figure 14: Model estimated total forestry sector plus substitution C (TFSC) as a function of selected parameters. a) Wood density, b) Biomass turnover c) Maximum volume, d) Thinning intensity, e) Rotation length, f) Product allocation, g) MRT of products, h) Products to energy flow, i) Product substitution factor, j) Substitution factor.

Since parameter variation is considered to be parameter-specific, absolute sensitivity of single parameters cannot directly be compared with sensitivity of others. Table 12 and Figure 14 put the model sensitivity to a parameter change into relation to the parameters variation for the same output variable (average change in total sector C and substitution). The values are averaged over seven model simulations. The ranking of most influential parameters changes when looking at relative influence. Wood density and maximum volume gain importance in timber and energy options. The table further reveals two groups of parameters that differ in their influence on total sector C and substitution change. Relative sensitivity values for thinning intensity, rotation length and start values for soil, litter and product pools have a negative signature. This indicates a negative relation of these parameters to the observed output variable: an increase in the parameter value leads to a decrease in change in the model variable.

Table 12: Results from analysis of relative sensitivity averaged over seven prescribed samples along the parameter range. Indices show the sensitivity of average change in total sector C and substitution with respect to a parameter change.

	Spruce			Beech	
	timber	energy	conservation	timber	conservation
Reference run	0	0	0	0	0
Wood density	0.846	0.847	0.650	0.855	0.708
Biomass turnover	0.134	0.112	0.258	0.143	0.219
Maximum volume	0.590	0.493	1.180	0.552	1.175
Thinning intensity	-0.084	0	0	-0.082	0
Rotation length	0.076	-0.141	0	-0.522	0
Product allocation	0.164	0	0	0.052	0
MRT of products	0.021	0.040	0	0.005	0
Products to energy flow	0.041	0	0	0.017	0
Product substitution factor	0.150	0	0	0.053	0
Substitution factor	0.406	0.697	0	0.512	0
Soil and litter start values	-0.264	-0.252	-0.505	-0.309	-0.443
Product start values	-0.152	0	0	-0.081	0
Soil and litter + product start values	-0.416	-0.252	-0.505	-0.390	-0.443

Table 13: Relative sensitivity of different model variables (levels of aggregation) to two parameters. Indices show the sensitivity of average change in the variable with respect to a parameter change.

Parameter	Variable	Spruce			Beech	
		timber	energy	conservation	timber	conservation
Maximum volume	TFSC	0.28	0.30	0.55	0.30	0.56
	Forestry sector	0.24	0.22	0.55	0.27	0.56
	Ecosystem	0.24	0.22	0.55	0.27	0.56
	Biomass	0.42	0.40	0.83	0.43	0.80
	Soil	0.02	0.01	0.11	0.05	0.14
	Products	0.44	0.53	0	0.48	0
Rotation length	TFSC	-0.05	0.03	0	-0.21	0
	Forestry sector	0.13	0.36	0	-0.09	0
	Ecosystem	0.28	0.37	0	0.02	0
	Biomass	0.46	0.56	0	0.06	0
	Soil	0.08	0.15	0	-0.04	0
	Products	-0.97	-0.68	0	-2.66	0

All parameters have an influence on carbon in forestry sector pools and substitution if the forestry option includes the related processes or pools. Table 13 splits total sector C and substitution into contributing perspectives and shows relative sensitivity for two parameters as an example. The influence of parameter maximum volume has a direct impact on biomass and is different for different pools and different levels of aggregation. It is highest for biomass and products and lowest for soil. Rotation length influences biomass and soil positively but products negatively. The impact on model output is still negative.

The results of the sensitivity analysis give helpful insight into the forestry model. Among the parameters chosen for analysis, sensitivity of changes in C stocks is high for parameters affecting biomass (maximum volume and wood density) and the yield of substitution (energy substitution factor). While wood density incorporates often uncertainty that is known and can be measured, the substitution factor and also maximum volume sum up a large number of processes with usually less known ranges. The latter were therefore associated with a higher assumed uncertainty. For better comparison of parameters with different uncertainty a measure is needed to qualify differences. Relative sensitivity emphasized the importance of wood density and maximum volume.

A comparison with the absolute parameter change plotted against induced variable change (Figure 14) shows that some of the parameters have a clearly linear relation to model output variables like wood density and substitution factor. These parameters are also most influential. This finding is important for the estimation of uncertainty propagation through the model. If uncertainty of parameters with linear relation to model output is known, model output uncertainty can be assessed much more easily. Changing rotation length creates a non-linear change in the model output. On average, the response is negative for spruce for energy and beech for timber. An increase in rotation length yields a reduced total forestry sector C and substitution indicating that with longer rotation more C is lost to the atmosphere through decay of plant material that could have been used to substitute fossil fuel C (in the case of spruce) or stored in long lasting products (in the case of beech). Average change in total forestry sector C and substitution decreases also with increasing thinning intensity. Unlike harvest of mature trees, thinning activities transfer comparably large parts of living biomass as slash material to the litter and soil pool. Aiming at climate change mitigation through an intensification of thinning therefore needs to include a change in the treatment of thinning removals, e.g. towards the use for bioenergy production.

To interpret the results of the hierarchical clustering, a comparison of the dendrogram (Figure 15) with Table 12 is helpful. The values of relative sensitivity were therefore printed next to the 'leaves' at the tree.

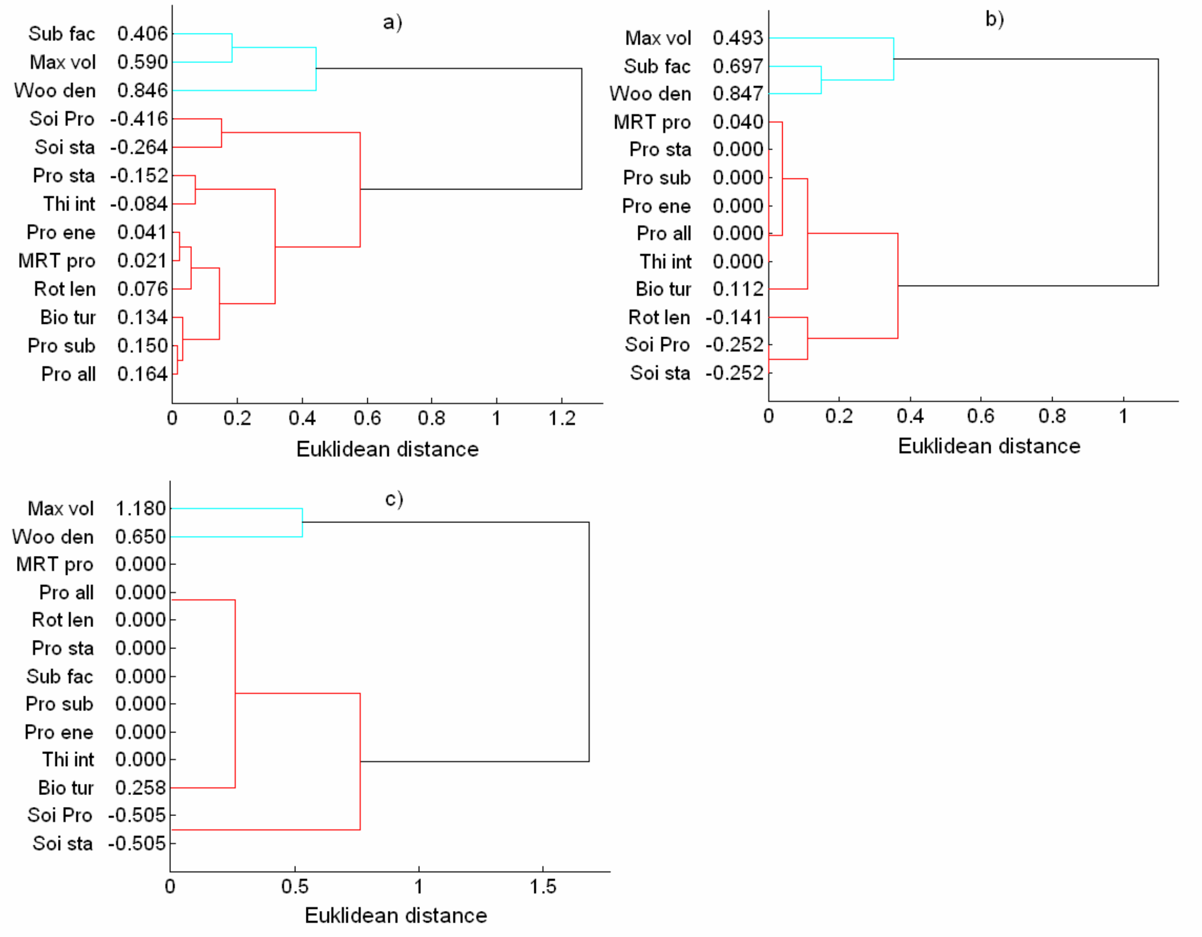


Figure 15: Dendrogram based on a complete-linkage clustering of the Euclidian distance of relative sensitivity of modeled average change in TFSC to an introduced range in 13 model parameters (only spruce forestry options: a) Spruce timber, b) Spruce energy, c) Spruce conservation). Colors mark different clusters. Labels include parameter name in short and relative sensitivity values (see Table 12 for reference).

The dendrogram in Figure 15 summarizes the results of the sensitivity analysis in a comprehensive way. It groups parameters with similar effect on modeled changes in total sector C and substitution. Parameters with similar values of relative sensitivity are contiguous in the dendrogram. Substitution factor, maximum volume and wood density are clearly distinct from the large cluster of all other parameters. Also clustered are product related parameters like product substitution factor and mean residence time in product pools. Their influence is similar with respect to a comparably small impact on the model output variable.

FOUR.3.2 Model uncertainty on landscape level

In 500 model runs all 13 parameters were changed randomly along a Normal distribution. Figure 16 describes the frequency distribution of four different output variables as a result of parameter uncertainty. Figure 17 provides the associated standard deviation for different pools and levels of aggregation. We see standard deviation increasing with perspective from biomass to ecosystem, forestry sector and total sector C and substitution. For comparison the figure shows the sum of standard deviation for each pool included in the level. Most of the standard deviation is driven by biomass. The fraction of C in pools added increasing level of aggregation is more than the added fraction of standard deviation. As a consequence, the relative standard deviation decreases with level of aggregation.

As models are qualitatively different (simple or complex, stochastic or deterministic, average or spatially explicit, etc.) uncertainty in the input data is differently dealt with. We introduced uncertainty in parameters to FORMICA with the help of Monte Carlo simulations. The Normal distribution shape of parameter uncertainty is clearly reproduced in the model output which can also serve as an indicator that the processes represented in the model are mostly of linear nature. However, skewness of the frequency distributions in Figure 16 was slightly negative, indicating that the data are spread out more to the left of the mean than to the right and pointing to non-linear relationships (e.g. maximum volume and forest growth).

Besides an insight into model structure and sensitivity of model output to certain parameters the analysis revealed the importance of distinguishing between different types of uncertainty with regard to modeling. There is uncertainty in the data, i.e. in initial values and parameters. Data uncertainty usually results from uncertainty of observations where initial values and parameters are derived from. For some parameters uncertainty can be quantified and be constrained to a certain range or distribution. Such an uncertainty can be considered by the model and included in calculations.

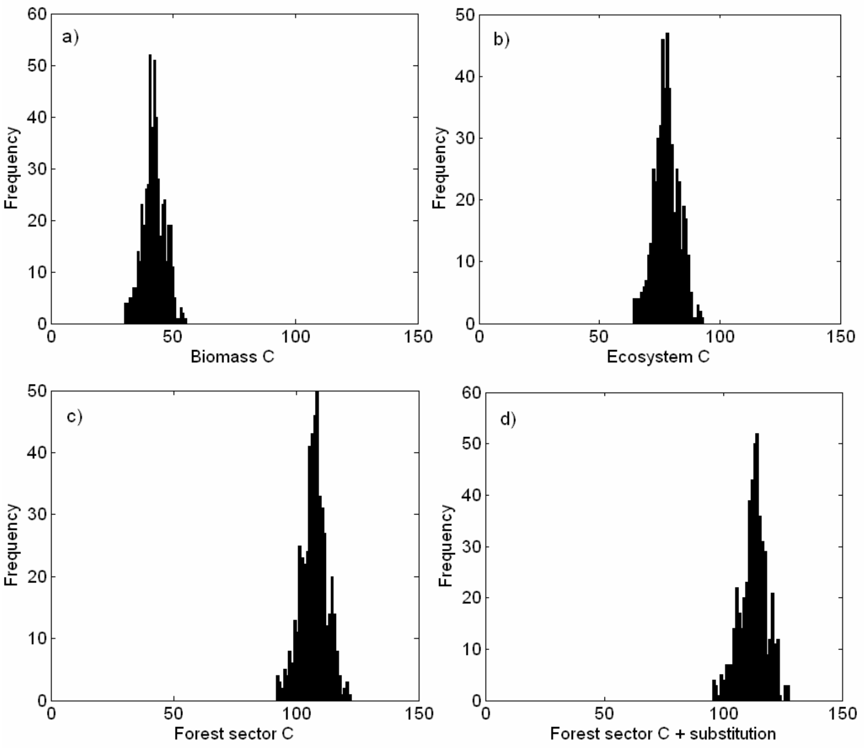


Figure 16: Absolute frequency distribution of 500 Monte Carlo simulation runs for four output variables of the Thuringian C balance: a) biomass C, b) ecosystem C, c) forest sector C and d) forest sector including substitution (TFSC) in tones of C per ha, averaged over a 60 year simulation period. Skewness = -0.05, -0.01, -0.16 and -0.3.

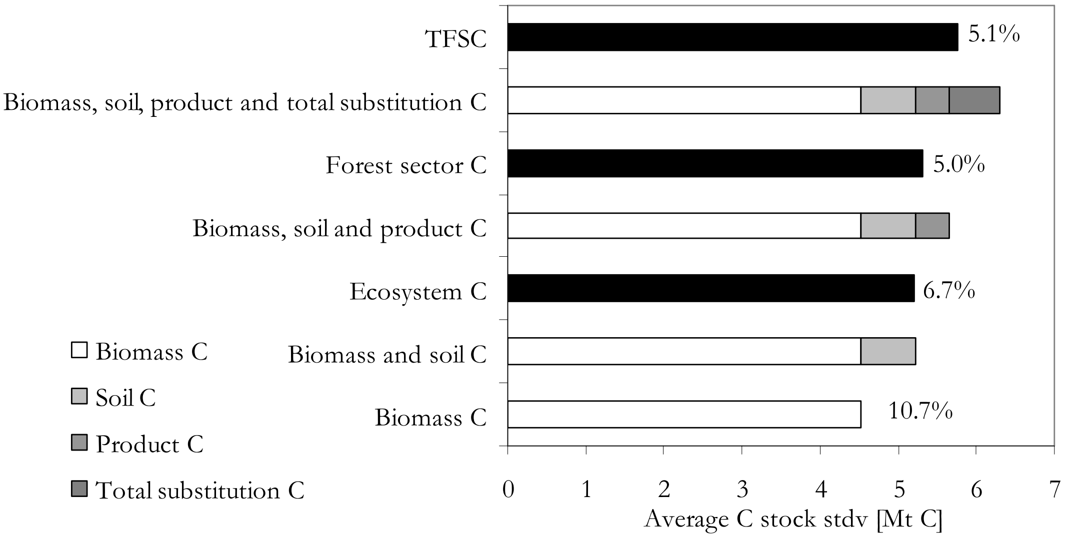


Figure 17: Average C standard deviation for different pools and levels. Data labels give relative standard deviation (standard deviation/mean*100). TFSC = total forest sector including substitution.

Another issue is uncertainty propagation through model structure. We already observed that variable sensitivity to parameter change can have two directions: positive or negative. Table 13 reveals that this relationship can change between different model variables, here C pools. A prolongation of rotation length has a positive effect on forest biomass but a negative on harvested wood products and related substitution of fossil fuels. The opposite effect occurs when rotations are shortened. Both effects can not be separated because one conditions the other. When product C is added to biomass C on ecosystem level, the positive effect of rotation length is offset by its counterpart, decreasing the range of uncertainty of the controlling parameter, here rotation length. Figure 17 nicely demonstrates the effect of aggregation on uncertainty. Standard deviation increases with higher levels of aggregation while deviation relative to the mean decreases up to the forestry sector level. On the one hand, this is due to inclusion of processes with relatively smaller uncertainty, in other words: relatively more C than uncertainty is added. The more pools are incorporated in the landscape C balance, the more processes and thus parameters and their uncertainty are included. However, on the other hand, it might be that processes with large uncertainty but different signature are summed up. This can be concluded from the fact that the sum of uncertainty of the included pools on each aggregation level taken separately is bigger than incorporated uncertainty.

FOUR.3.3 Effects of projected management change versus uncertainty

Currently managed forests in Thuringia are a strong sink. Table 14 sums the potential stock increase in forest carbon, products and substitution on different levels of integration for the period of 2010 to 2050. Within these 40 years, biomass carbon could increase by more than 9 Mt C under continued Business as Usual. The ecosystem however, would gain less due to slight decrease in litter and soil C. Also product pool loses C, which is expressed by lower values if the perspective is on the forestry sector level. This is due to the relatively large proportion of younger forests in Thuringia. However, including substitution of fossil fuels during the respective period of time would double mitigation potential. Highest values of C capturing can be achieved with conservation and species change but differences between management options emerge on lower levels of aggregation.

Table 14: Mitigation potential in Thuringia for Business as Usual and assumed management change scenarios for a 40 year period (2010-2050) aggregated on different levels (implementation on 20% of forest area). TFSC = total forest sector including substitution.

	Potential [Mt C] 2010-2050			
Scenario	Biomass C	Ecosystem C	Forest sector C	TFSC
Business as Usual	9.2	8.7	7.7	18.0
Longer rotation	10.1	9.9	8.1	17.9
Shorter rotation	7.9	7.3	7.0	17.3
Species change	13.3	13.2	11.2	21.0
Conversion	9.4	9.0	7.1	16.8
Conservation	13.7	13.6	10.6	19.9

The model results of possible management change and projections under Business as Usual are displayed over time in Figure 18. All scenarios except the one of shorter rotations gain carbon in biomass during the 60 years simulation period. Overall differences between scenarios are comparably small compared to the estimated uncertainty, especially when looking at the 20% implementation level. High C stocks throughout the entire simulation period can be observed from conservation and species change. Only in these two scenarios, biomass stocks move beyond the standard deviation of the business as usual scenario within few decades. While biomass is a strong sink other pools like soil and litter and products on average lose carbon in all scenarios and thus diminish the sink strength on the ecosystem or forestry sector level (Table 15).

Table 15 gives averages of the difference of each management change scenario compared to Business as Usual for different levels of aggregation. Including more pools in the C balance of Thuringia would lead to even higher uncertainty. The difference in the C balance of management change gets smaller with higher levels of aggregation. Conversion is an exception. Higher aggregation means that differences between management options that often impact pools contrarily diminish. Longer rotation and shorter rotation are barely distinguishable on the level of total forestry sector and substitution C from each other and Business as Usual because their differences simply imply different allocation patterns from biomass C to product C over time. Evidently, carbon is treated similarly in these pools so that big discrepancies between the options only become apparent if pools are excluded.

Table 15: Average C stock in t C per ha of Business as Usual, differences of management change scenarios to Business as Usual and uncertainty range of Business as Usual over 50 year simulation period aggregated on different levels (20% implementation).

Scenario	Biomass C	Ecosystem C	Forest sector C	TFSC
		[t C ha^{-1}]		
Business as Usual (BaU)	43.7	79.6	118.4	126.7
Uncertainty range of BaU	4.5	5.2	5.3	5.8
Longer rotation difference to BaU	0.4	0.5	0.09	-0.2
Shorter rotation difference to BaU	-0.6	-0.7	-0.2	-0.2
Species change difference to BaU	2.3	2.5	2.0	1.7
Conversion difference to BaU	0.03	0.04	-0.5	-0.8
Conservation difference to BaU	2.6	2.7	1.6	1.0

Comparing the development of stocks and stock changes suggested by the model with projected uncertainty shows that management changes need to be large to be separated from uncertainty (Figure 18). Focusing only on biomass C, only two realistic management change options, namely conservation and species change produce signals over the 50 year simulation period, which are large enough to go beyond model uncertainty. When implementation level rises, management change signals get relatively stronger (Figure 18a vs. b) compared to growing uncertainty. An implementation level of 100% is purely theoretic and far from realistic. Still, this exercise shows clearly the proportions between projected impacts of management change and assumed uncertainties.

When C pools are aggregated over the simulation period, the C pool changes induced by management changes are small compared to the standard deviation of the Business as Usual scenario. This results from the fact that only a small fraction of the total forest area changes, which is diluted in the large remaining unchanged fraction. This does not mean, however, that in practice, these changes would not be detectable by inventories or field surveys in case the locations where changes occur are known.

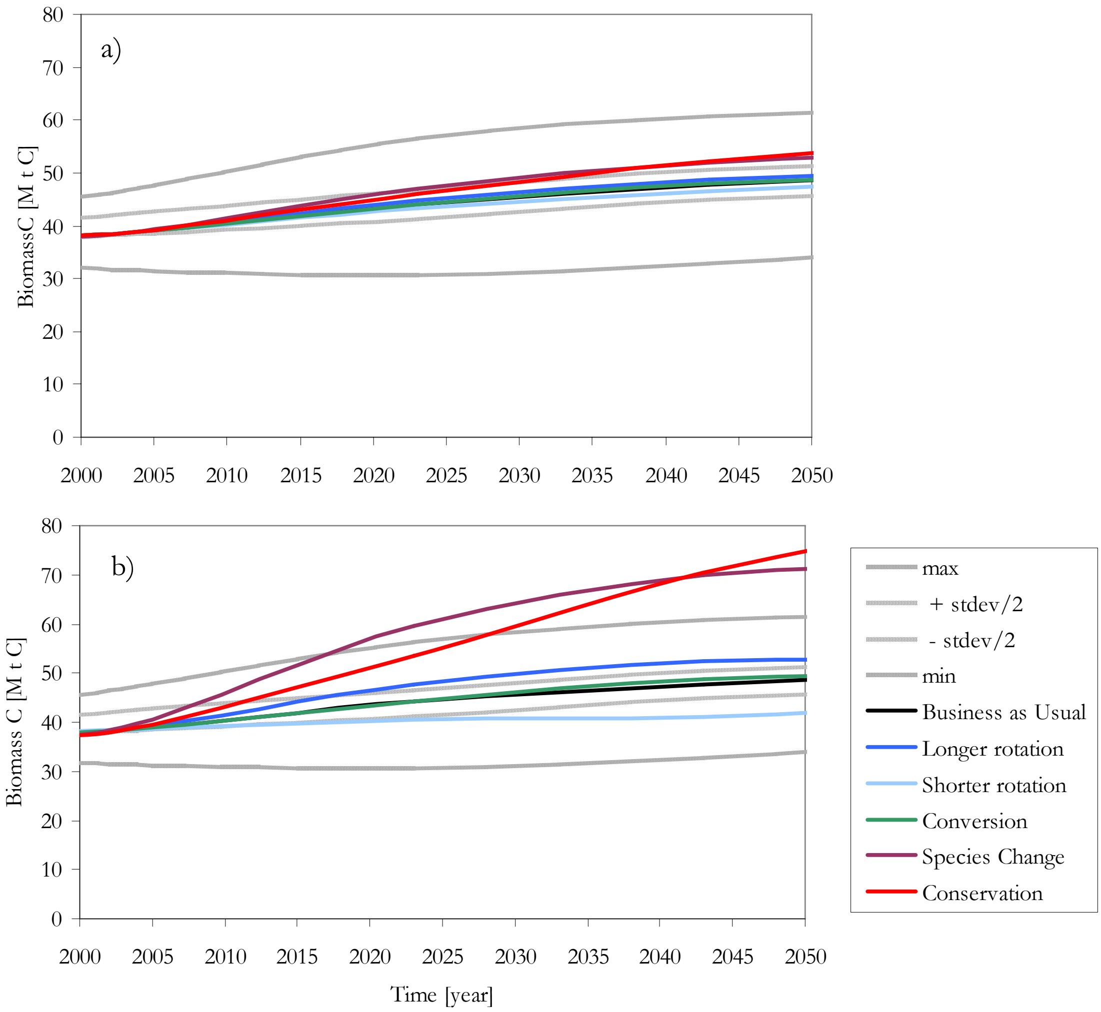


Figure 18: Implications of management change on the development of Thuringian biomass C stocks in two variations: a) 20% implementation, b) 100% implementation. Grey lines give maximum, minimum and higher and lower range of standard deviation. Only 50 years of the 60 years simulation period are shown.

The uncertainty projected by FORMICA changes over time for biomass C. This is because the initial values (stem volume) were considered to have an externally prescribed uncertainty of 10%. Treated over time, these variables are subject to uncertainty of parameters controlling them that were not considered in the initial conditions. If initial uncertainties would be bigger than average uncertainties over time, the model would predict a decrease. It can be assumed that processes in the future get more uncertain the further they are. Looking from the starting point of model simulation into the future, an increasing uncertainty over time seems more plausible.

The study did not incorporate uncertainty of all parameters. The most influential parameters, however, were captured and the uncertainty level of the ones included was relatively high. The overall uncertainty might therefore be close to what was presented here. In fact, forestry is driven by more parameters and more complex processes like markets and policy that could not be included in FORMICA. Changes in carbon stocks induced by management change on 20% of the area were compared against a large background uncertainty of the entire forest area. This criterion is relatively hard for assessing the significance of management change. However, when it comes to an accounting of management-induced CO_2 mitigation measures under a policy framework the reference baseline might be narrower than that background. This issue will be further elaborated on in the following chapters.

FOUR.4 Conclusions

There are many biotic and abiotic factors which influence forest ecosystem (forest growth, biomass turnover, decomposition) and forestry sector (product use, efficiencies) mitigation services. All processes contribute their share of uncertainty. Forest management adds another component with numerous aspects to these processes. We used the forestry model FORMICA to highlight sensitive parameters which control different processes in different parts of the forestry sector C balance, e.g. maximum biomass controlling forest growth and the energy substitution factor controlling the yield of fossil fuel displacement.

Uncertainty exists of different kinds. Some parameters might be well constrained in a certain distribution, the range and distribution of others might be less certain. FORMICA can read in parameter uncertainties of known distribution and include them in C balance calculations with the means of Monte Carlo simulations.

Model sensitivity to certain parameters, e.g. rotation length might change signature in different variables. Such parameters may decrease C stocks in one pool and necessarily increase C in others (e.g. rotation length decreases biomass C when it is shortened but increases carbon stored in products). This leads to the special feature that overall uncertainty might decrease with the level of aggregation. These special features of uncertainty of C stocks and stock changes in the forestry sector that were presented here have to be considered in carbon reporting and accounting.

In the case study of Thuringia projected stock changes related to some management change options on a realistic implementation level did not exceed the uncertainty band. Higher level of implementation but not higher level of aggregation can improve model predictions in terms of uncertainty. It is crucial to incorporate uncertainty in model estimations of future forest sink development and management change projections. Model sensitivity analyses can then help to identify important parameters that need to be constrained sufficiently to reduce uncertainty of model output.

FIVE

ACCOUNTING OF FOREST MANAGEMENT UNDER A FUTURE CLIMATE PROTOCOL AND FACTORING OUT OF PAST PRACTICE EFFECTS

FIVE.1 Introduction, aims and scope

Atmospheric measurements indicate the presence of a terrestrial sink for carbon dioxide (CO_2, Schlesinger, 2006) partly offsetting emissions from land-use change and combustion of fossil fuels. The magnitude of this flow amounts to approximately one third of the annual anthropogenic emissions from fossil fuel burning (IPCC, 2007) but is still associated with large uncertainties. Current research assumes that the sink can be partly explained by the reaction of the terrestrial vegetation to climate change (Cao et al., 2005, Joos et al., 2002), increasing CO_2 concentration (Norby et al., 2005; Körner, 2006; Moore et al., 2006; Reich et al., 2006), and increasing nutrient deposition (De Vries et al., 2006). However, there is also evidence for a large contribution by regeneration of forests especially in the United States and Europe (Kohlmaier et al., 1995; Caspersen et al., 2000; Goodale et al., 2002). This is a consequence of changes in forest management and its intensity compared to the past. The influence of past practices is maintained for decades after changes in the management regime occurred and is likely to determine regional future carbon dynamics of the biosphere more than other contributors. Estimates of the fraction of the forest sink due to management change vary widely but are quite high (40 – 98%, Houghton 2003).

The Kyoto Protocol under the United Nations Convention on Climate Change (UNFCCC) commits industrialized countries to reduce their GHG emissions in the period of 2008 to 2012 by roughly 5% compared to emissions in 1990. The negotiating parties created an option for countries to elect activities in land-use, land-use change and forestry (LULUCF) to be accounted for. Article 3, paragraph 4, of the Protocol allows to choose any of forest management, cropland management, grazing land management and revegetation activities for meeting its commitments (UNFCCC, 1997).

The national forest C sources and sinks are reported, according to IPCC Guidelines, as the total of C stock changes in managed forests, as they occur in the reporting period, including all sorts of disturbances and harvest, often based on forest inventories. The rule differs for the accounting of forest C sinks under Article 3.4 of the Kyoto Protocol. In the 'Marrakesh Accords' the Conference of the Parties (COP) in 2001 agreed that only directly human-induced fluxes shall be accounted for and to exclude natural and indirect human-induced effects from the accounting: in particular the effect of (a) elevated CO_2 concentrations above pre-industrial levels, (b) indirect nitrogen deposition, and (c) the dynamic effects of age structure resulting from activities prior to 1 January 1990 (Marrakech Accords: FCCC/CP/2001/13/Add.1, English, Page 55 and FCCC/CP/2001/13/Add.3, English, Page 23, UNFCCC, 2002). Within the Kyoto framework the problem of factoring out of past practices and other indirect effects was circumnavigated by introducing national caps for the maximum accountable sink (or source). Through this simple measure, accountable amounts in the first commitment period were, in theory, limited to 15% of the reported sink from forest management (Höhne, 2006). The discount was subject to negotiation for some countries and changed several times throughout the negotiation process. As a result the allowed amounts often do not align with forest area or reported sinks or removals from forest management (e.g. the cap for Japan (13 Mt C per year) is larger than the one for Canada (12 Mt C per year), see Table 16). Art. 3.4 Forest Management was recently adopted for the first commitment period by many Annex-I countries (see also Table 16) and is expected to be widely accepted as eligible measure in a future climate protocol.

The issue of factoring out indirect human-induced forcings of the carbon cycle like elevated CO_2 or nitrogen deposition has been addressed in various studies (Vetter et al., 2005; Canadell et al., 2007a). The separation of fluxes as either anthropogenic or non-anthropogenic remains problematic (IPCC, 2003a). Unlike indirect human-induced and natural effects (see points (a) and (b) above) on GHG exchange between atmosphere and terrestrial biosphere, which can be studied with control sites on experimental plots, effects of past practices as mentioned under point (c) emerge only at landscape level. They can only be quantified with the help of inventories and detailed knowledge of past disturbances and harvest. While technical solutions to the problem of factoring out may become available in the coming years, the issue of an appropriate accounting remains unsolved.

Here, more sophisticated conceptual approaches are presented, combined with a model-based assessment of implications of choices of approaches for accountable C sinks and sources. In a modeling experiment, general effects of age-class structure on the recent and future regional carbon balance of managed forest ecosystems are examined with the help of a forestry model. The exercise will focus on biomass C stocks and stock changes, where impacts are most clear. The results are used to point out general consequences for the accounting under a future climate protocol.

Table 16: Parties of the Kyoto Protocol and their decision on Article 3.4 Forest Management, limits for accounting net removals for forest management under Article 3.4, reported emissions from LULUCF in 2004 and forest area from FAO Forest Resource Assessment 2005 (FAO, 2005). *) Added with decision 22/CP.9, **) Changed from originally 17.63 by decision 12/CP.7 *) FCCC/SBSTA/2006/L.6/Add.1**

Party	3.4 FM elected?	Cap [Mt C yr^{-1}]	Reported LULUCF emissions 2000-2004 [Mt C yr^{-1}]	Forest area [1000 ha]
Australia	no	0.00	2.8	163678
Austria	no	0.63	-4.5	3862
Belarus	no	-	-3.8	7894
Belgium	no	0.03	-0.6	667
Bulgaria	no	0.37	-5.5	3625
Canada	no	12.00	-24.4	310134
Croatia	not reported	*0.265	-4.9	2135
Czech Republic	yes	0.32	-1.8	2648
Denmark	yes	0.05	-0.1	500
Estonia	no	0.10	-4.7	2284
Finland	yes	0.16	-4.9	22500
France	yes	0.88	-11.8	15554
Germany	yes	1.24	-9.5	11076
Greece	yes	0.09	-1.3	3752
Hungary	yes	0.29	-1.1	1976
Iceland	no	0.00	0.4	46
Ireland	no	0.05	0.0	669
Italy	yes	***2.78	-29.5	9979
Japan	yes	13.00	-23.2	24868
Latvia	no	0.34	-3.8	2941
Liechtenstein	no	0.01	0.0	7
Lithuania	yes	0.28	-2.4	2099
Luxembourg	no	0.01	-2.6	87
Monaco	no	0.00	0.0	0
Netherlands	no	0.01	0.7	365
New Zealand	no	0.20	-5.7	9387
Norway	no	0.40	-7.2	9192
Poland	yes	0.82	-85.5	3783
Portugal	yes	0.22	-1.2	329
Romania	yes	1.10	-10.0	6370
Russian Federation	yes	**33.00	0.0	808790
Slovakia	no	0.50	-1.2	1929
Slovenia	yes	0.36	-1.4	1264
Spain	yes	0.67	-8.5	17915
Sweden	yes	0.58	-4.7	27528
Switzerland	yes	0.50	-12.0	1221
Turkey	not reported	-	-58.9	10175
Ukraine	yes	1.11	-10.7	9575
United Kingdom	yes	0.37	-0.2	2845

Available accounting rules will be presented and evaluated whether they a) ensure a close relation of accounting to observable/measurable stock changes and thus facilitate verification; b) provide incentives for improving forest management.

FIVE.2 The legacy effect of past disturbances

A common way to describe a forest landscape is by age-class distribution. This shows the area covered by groups of forest stands or sections that have the same age or lie within the same range of ages. The age-class structure is also a mirror of the past because it can be recalculated how much forest area has been established or regenerated at a certain point in time. With the help of models, the development of age-class structure can be projected into the future if certain parameters are known. The operational Carbon Budget Model of the Canadian Forestry Sector (CBM-CFS 3, Kurz et al., 2002) was used in the following modeling exercise.

FIVE.2.1 The evolution of age-class structure

Let us assume that in three experimental forests disturbances and ecosystem recovery are constant over time. One forest is disturbed by harvest, one by insects and the last by fire. To simplify, it is assumed that all disturbances are stand replacing. Disturbance parameters are listed in Table 17. Every year the same sum of area is disturbed and all forest age-classes are affected with a certain probability, which is also constant. The disturbance rate, i.e. the average annual area disturbed, is determining the size of the youngest age-class observed. It is the sum of the area disturbed during the time of an age-class width.

Table 17: Description of disturbance types and parameters used in CBM-CFS3 to simulate the impact of constant disturbance regimes on age-class structure. The model was run for at least 1000 years or until age-class structure was stable.

Disturbance type name	Description	Annual sum of area disturbed	Youngest age-class affected	Selection criterion
‘Harvest’	Highly selective harvest targeting merely stands older than 100 years	1%	100	oldest first
‘Beetle’	Stand replacing disturbance of randomly chosen stands above age 50	1%	50	random
‘Fire’	Stand replacing random disturbance of all age-classes	1%	all	random

The selectivity on the other hand forms the basic shape of the age-class structure. In systems where all age-classes have the same probability to be disturbed and the disturbed area per age-class is relatively small, the age-class distribution after long-lasting constant disturbance follows a negative exponential, left shifted distribution ('Fire' in Figure 19, Van Wagner, 1978). This is because older age-classes have been subject to disturbance more often than younger stands. Their area declines as they get older over time. An example of this type of disturbance are wild fires in Canada (Li and Apps, 1995; Huggard and Arsenault, 1999). The assumption made in this theoretical experiment, that fire affects all age-classes without any priorities, applies probably only for very few forest types. In many natural forest landscapes early successional stages are dominated by fire inhibiting broadleaved species (Bergeron et al., 1998). These would lead to more complicated age-class structures as suggested in this theoretical example.

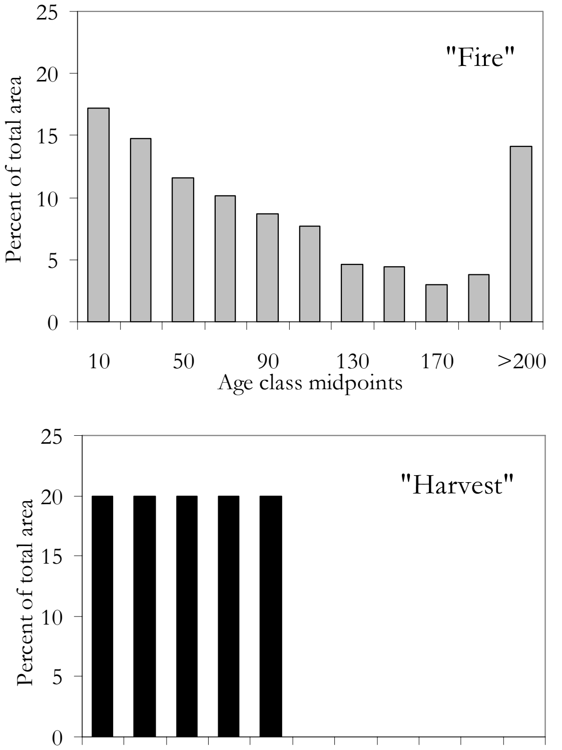


Figure 19: Three cases of different age-class structures: landscape as a result of different disturbance patterns. 'Fire' is the product of a constant random fire disturbance; landscape 'Beetle' was subject to a permanent disturbance through insects attacking merely stand that are older than a certain age. 'Harvest' is a result of constant harvest above a certain age (100 year). Age-class width is 20 years except the last age-class which contains all area > 200.

An intensively managed rotation forest can be seen as an example of a highly selective disturbance system, targeting exclusively all stands older than the threshold age determined by the rotation time. The result of this type of disturbance is the distribution referred to as the 'Normal Forest distribution', an equal distribution in which every age-class covers the same area. Between these extreme cases (random selectivity and high preference) more complex systems can be imagined, where more than one type of disturbance is present or where disturbances are subject to a certain range of age-classes (e.g. insect disturbance which occurs only in trees of a certain diameter). The age-class distribution would then be of an s-shape ('Beetle' in Figure 19).

All systems described above have one feature in common. They are all either equally distributed or left shifted. Under constant disturbance regimes, when the age-class structure is in equilibrium, there is no age-class distribution that is right shifted, i.e. has fewer young than old stands. The age-class distribution of a landscape with fewer stands in young age-classes is not sustainable. The age-class distributions described above are ideal, conceptual situations. In reality, the age structure of forests will unavoidably change over time and is therefore an indicator of past or recent changes in disturbance regimes.

Considering the relationship between disturbance regime and age structure as described above, the method does help to reconstruct past disturbance return intervals. However, what is usually observed in the field is in most cases a fuzzy age structure with many processes having contributed to and which were subject to management and disturbance change over time. In addition, forest area might have changed through afforestation or deforestation, introducing another source of uncertainty. Different histories of disturbance might lead to similar age-class distributions, making such an 'inversion' impossible.

FIVE.2.2 Effects of age-class structure on the carbon budget

We consider now three other forest landscapes that differ only in their age-class structure (see Figure 20). Landscape LS is characterized by a left shifted age-class structure, e.g. as a result of fire or increasing afforestation rates in the past. Landscape NF is a typical 'Normal Forest' with an equal distribution of age-classes like in an ideally managed plantation. A transient case is represented by landscape RS, a right shifted distribution that is a product of changes in disturbance regimes. It was created by a period of high disturbance rates followed by a period of lower disturbance rates. We further assume that carbon stocks for different age-classes follow – like in a chronosequence – a function over age, where young stands hold relatively smaller carbon stocks compared to old stands. To simplify the experiment the average ecosystem carbon stocks per age-class are considered to be the same for all landscapes, i.e. all landscapes have the same underlying carbon curve.

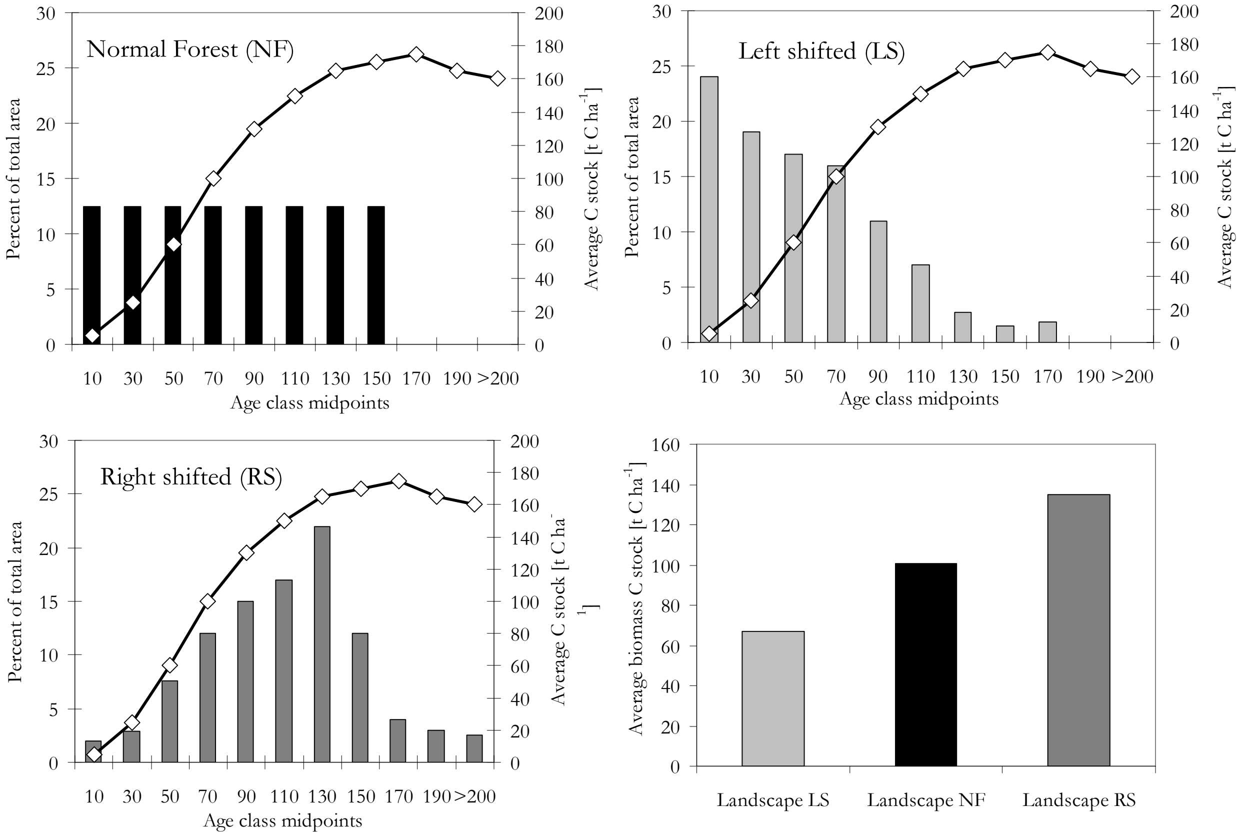


Figure 20: Three forest landscapes with different age-class structure: landscape NF shows an equal distribution of age-classes as observed when management is constant over a long period of time and random disturbance is absent; landscape LS represents a region dominated by young forests, e.g. formed by an increasing area of afforestation during the past; the structure is left shifted; a lack of young forest shifts the age structure of the third region (landscape RS) to the right, this structure can only develop when disturbance changes, e.g. a drop in area annually disturbed; the bottom right panel shows different landscape carbon stocks for three of the presented landscapes as a result of different age-class distribution. Age-class width is 20 years.

Summing up the landscape carbon budget, the RS landscape contains 1.3 times the ecosystem carbon of the LS landscape age-class structure. This is only due to differences in the age structure and due to the fact that average carbon stocks vary with stand age. The landscape carbon budget of a forest region is determined by these two factors: a) the average carbon density per age-class and hectare multiplied and weighted by b) the area in each age-class (i.e. the age-class structure). Both also influence the future carbon dynamics on that level. Both factors are the result of disturbances the landscape was subject to in the past. But they were formed through different processes and follow very different rules in their dynamic over time.

FIVE.2.3 Effects of age-class structure on carbon dynamics over time

The focus will now switch to implications on the development of C stocks over time. Regardless of their history, the same management will be applied to the three test areas RS, NF and LS introduced above. Constantly 0.63% of the area will be harvested annually in a clear-cut system targeting at the oldest age-classes. This is equivalent to a rotation length of 160 years. Continuous management without any natural disturbance and no market influence will always lead to a balanced age-class structure (NF). This has the following consequences for the three landscapes underlying this management: the RS landscape looses biomass carbon, the NF landscape is 'neutral' and the LS landscape gains biomass carbon until they all reach the same equilibrium state of landscape carbon stocks and age-class distribution (Figure 21).

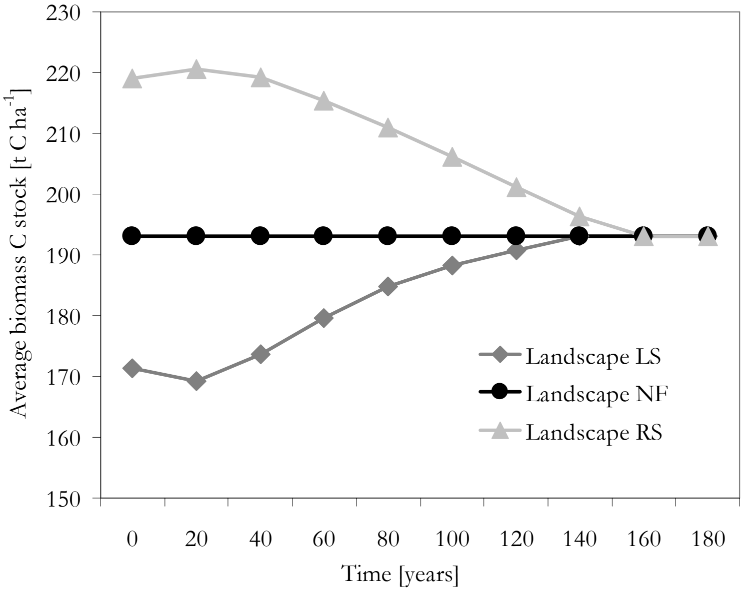


Figure 21: Resulting total ecosystem carbon stock development over time if the same management is applied to the three landscapes that just differ in their age structure (LS left shifted, i.e. young; NF Normal Forest and RS right shifted, i.e. old).

Age-class structure RS is not sustainable under the currently applied management as described above. The RS landscape is bound to lead to declining carbon stocks at some time in the future. And although managers of landscape LS and RS apply the same management, landscape LS would create credits under Kyoto while landscape RS creates debits.

The model exercise included only biomass C to simplify things. Impacts of disturbance and harvest are more straightforward for the biomass pool compared to dead organic matter and soil C. However, an inclusion of additional pools in the analysis would simply introduce a delay of changes in carbon stocks but eventually lead to the same situation.

FIVE.3 The problem of accounting

FIVE.3.1 Criteria for an adequate accounting

A recent publication of the German Federal Environmental Agency (UBA)[3] suggests criteria to be applied to an evaluation of options under a future climate regime. According to these criteria, an evaluation of methods for the accounting of forest management carbon sinks and sources under Article 3.4 needs to be consistent with goals of the UNFCCC. One of the most important criteria is therefore climate effectiveness. This includes an acknowledgement of the special characteristics of LULUCF activities within the carbon cycle. Being congruent with the aims articulated in UNFCCC means also that the accounting needs to provide incentives to lower sources and strengthen sinks for carbon. The approach should as well minimize the potential for loopholes.

Technical effectiveness of the approach is necessary to facilitate monitoring, accounting and verification of compliance. This includes the consistency with UNFCCC reporting rules, but does not necessarily mean that it has to be in line with the accounting methodology as prescribed for the first commitment period. Further, the proposed scheme needs to be cost-efficient when it comes to implementation, easy and cheap to monitor, and would be best based on existing data, i.e. forest inventories. Forest inventories contain sufficient information for carbon accounting if it is assumed that all C stock changes in the forest are accounted (as in UNFCCC reporting). An approach

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[3] Kyoto-Protokoll: Untersuchungen von Optionen für die Weiterentwicklung der Verpflichtungen für die 2. Verpflichtungsperiode, Teilvorhaben „Senken in der 2. Verpflichtungsperiode. FKZ 203 41 148/02

including forestry models in addition to inventories can account for the dynamic reaction of ecosystems to management and disturbances and allow for factoring out of processes that should not be accounted for.

FIVE.3.2 Choice of reference

Article 3.4 of the Kyoto Protocol implies that credit and debit will be based on a comparison between two points in time (Sampson and Scholes, 2000). Such a comparison could be done in several ways.

1) The first possibility suggests the accounting of the observed stock changes since the beginning of the commitment period ('gross-net'). C stocks at the beginning of the respective commitment period would serve as a reference. This leads to a full accounting of all C stock changes during the commitment period against none in the reference period. It is used for the accounting of sinks and sources from activities elected under Article 3.4 (see Introduction, Box 2). These can be large e.g. if the attribute 'human-induced' can be given to the driving forces and are therefore significant for setting emission limitation targets (caps). An advantage of this type of accounting is the very close relation to the actually occurring stock changes in ecosystems and forestry pools. This way of accounting also leads to a higher valuation of C stock changes in LULUCF compared to GHGs in other sectors where the following approach is taken.

2) The 'net-net' approach includes a retrospective reference, the change in carbon stocks in a reference year, e.g. 1990. It would be very consistent and easy to implement this for LULUCF as well, and also most consistent with the UNFCCC reporting requirements and the atmospheric view. However, there is a problem regarding incentives for all countries with a left shifted (young) forest age-class structure, i.e. countries with large stock increases in the reference year but declining sink due to forest aging during the commitment periods (the first derivative of stocks is positive, but the second negative). This applies to many Annex-I countries (see Chapter Six). The approach is more favorable to countries with right shifted (old) age structure and those, where past losses decline (therefore also favorably discussed for avoided deforestation).

3) The third approach defines a 'prospective baseline' as reference. For the accounting of project-based activities, business as usual activities with associated emissions or removals, were suggested as baseline. Carbon credits or debits are given for the difference between this scenario and stock changes occurring under a new activity, awarding only the net effect of management change and additional activities. This could

create more incentives, but deviates from the observed C stock changes. The major challenge of this approach is the definition of a baseline. Business as usual is one of several baselines that might be chosen.

In the following this approach will be analyzed in more detail as an alternative or an accounting of forest management and to factor out past practices.

FIVE.4 Baseline concepts

One way of addressing effects of pre 1990 factors on age-class structures is the application of a baseline at landscape level. Now, approaches of how to establish a prospective baseline in an increasing order of model complexity are presented. First, baseline approaches are described that focus on average carbon stock in an idealized landscape. More complex approaches follow that include average age as an indicator of age-class deviation. Finally a dynamic trajectory is presented that describes age-class shift and transition over time.

FIVE.4.1 Average carbon stocks

A recent suggestion of an accounting scheme (e.g. Kirschbaum et al., 2001; Kirschbaum and Cowie, 2004) is based on Average Carbon Stocks (ACS) associated with different land-use and management types under similar ecological conditions (biosphere domains). For each biosphere domain, an average carbon density is determined, defined as the long-term average carbon density that would be attained over its typical land-use practice. A change of management would be credited or debited by comparing previous t_0 and new t_1 biosphere domain and apportioning the resulting average carbon stock change over a transition time (Figure 23, Kirschbaum et al., 2001). The basic parameters needed to establish this type of baseline are catalogues of biosphere domains and associated target values. The implementation of these baselines could be a ‘top-down’ establishment of a general nature by international bodies, individual project based, or even subject to negotiation among the parties. The implementation is relatively easy and cheap because the approach is not based on a detailed inventory.

To assure compliance, the tracking of individual land parcels that have undergone land-use change is necessary, also to avoid future reversal or non-permanence of the created C sink, e.g. by deviation from the baseline. Not only biosphere domain change, but also a change in management intensity needs to be accounted for.

According to this approach, stocks are considered to be in equilibrium at the start of the accounting: That is not the case in most regions with a long management history or where changes in the disturbance regime have taken place (Figure 23). A general catalogue of biosphere domains, valid for different countries and situations can not account for the complex starting point of countries that evolve from different management and disturbance history. If the start is complex (see model landscapes LS, RS above) the way to the target point is hardly straight nor linear, but complex as well.

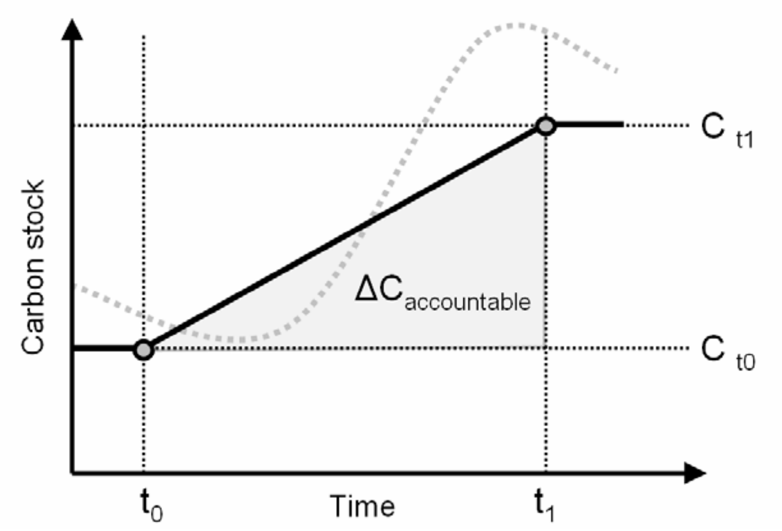


Figure 22 Average Carbon Stocks approach. Start carbon stock at point t_0 and target value at point t_1 are prescribed (grey dots), as well as the way there (black line). The difference between both values (grey area) is the accountable amount. An example of how actual stock changes might occur is described by the grey dotted line.

An accounting according to this approach would only cover the potential (static) stock changes in the case of land-use or management system change. Therefore this approach neglects the actually occurring carbon dynamics associated with past practices and thus fails to take into account actual carbon fluxes affecting the atmosphere. This leads also to difficulties in the verification of credits/debits claimed under this accounting approach.

The reference point in the accounting needs to reflect the complexity of landscape and management and disturbance history. Implicitly there is a typical age-class structure underlying every biosphere domain. The average carbon stocks per age-class might long be already in the new equilibrium while the age-class structure itself is not – affecting the landscape carbon budget (see Five.2.3). The transition between biosphere domains is thus more complex than expected and needs to include an age-related parameter. Any age-class effects are excluded from the accounting by the ACS approach because they are simply neglected.

FIVE.4.2 Average age

This concept is based on the assumption that the age-class structure of a forest landscape can be summarized in the single value of the average stand age. Average age is then used as an indicator of age-class transition. The catalogue of biosphere domains that could also be the basis for this approach would be extended by the relationship between average age and landscape carbon stock. The carbon curve in Figure 23 describes this relationship. It is the unweighted mean of carbon over age-classes. An observed change in carbon stocks from a start value at point t_0 with average age aa_0 to target value at point t_1 with average age aa_1 that is not related to a change in average age is accounted for. This concept could be used to partition between ecosystem aging and direct human-induced effects, like change in management intensity.

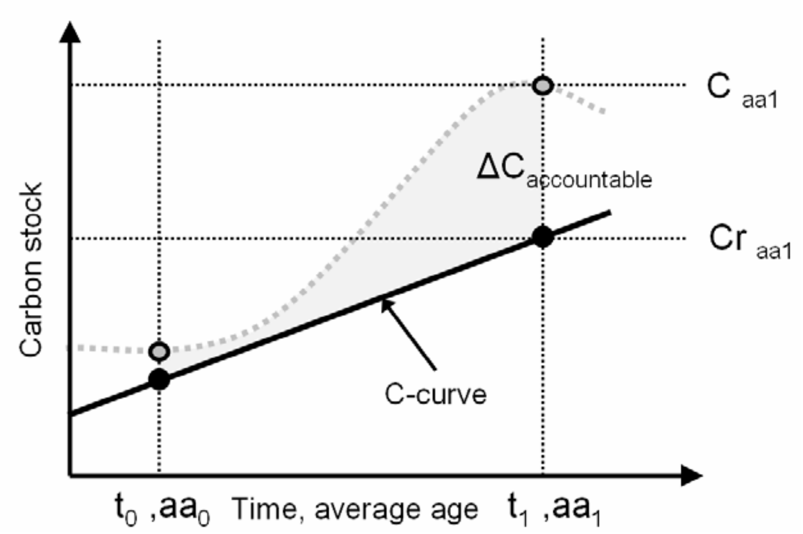


Figure 23: Average age baseline. Carbon stocks are related to average age of a forest landscape. An observed change in carbon stocks from a start value to target value (grey dots) that is not related to a change in average age (prescribed by the underlying C-curve, black line) is accounted for. NB! Time and average age on x-axis have different scales!

A problem with average age is that it summarizes age-class structure very simply. Few very old forests might compensate for many young forests. Very different age-class structures can thus lead to the same average age (cf. Figure 24). Another problem is the question whether an increase in average age does always imply an increase in landscape carbon stocks. The answer depends on the carbon curve that is underlying. A baseline based on average age can not reflect changes in forest area, e.g. due to land-use change. This would change the underlying C curve. It can merely account for effects of changing disturbance or harvest intensity.

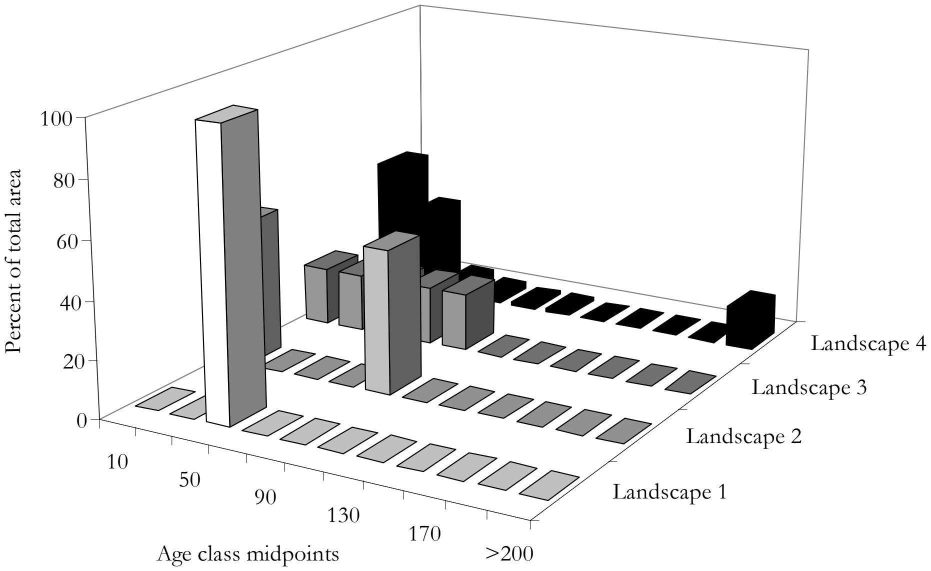


Figure 24: Extreme examples of four landscapes with extreme age-class distributions having all an average age of 50 years.

FIVE.4.3 Dynamic baseline

The application of the dynamic baseline approach on the landscape level that is currently used for accounting on project level can be realized with the help of regional forestry models. In general, the model is used to develop a reference scenario of C stock development over time that can be compared to other scenarios or measurements. Depending on the purpose, the reference scenario is based on certain parameters (e.g. rotation length, treatment of slash material) or initial conditions (e.g. age-class structure). The dynamic baseline is used in two examples: a) establishing a baseline against management change and b) establishing a baseline to factor out age-class effects.

A dynamic baseline to factor out Business as Usual

Knowing the current age-class structure, the model can produce trajectories of carbon stocks under a certain management or disturbance regime. Trajectories under a change in the regime can then be compared to the reference baseline scenario (Figure 25). Forestry models that are operating at the landscape level can produce any designed baseline, if disturbance parameters are known. A way to calculate effects of a management change would be a comparison of the management change scenario against business as usual. Both scenarios would use the same observed starting point. One simulates the presence, the other the absence of management change. The difference is the accountable amount of C stock change.

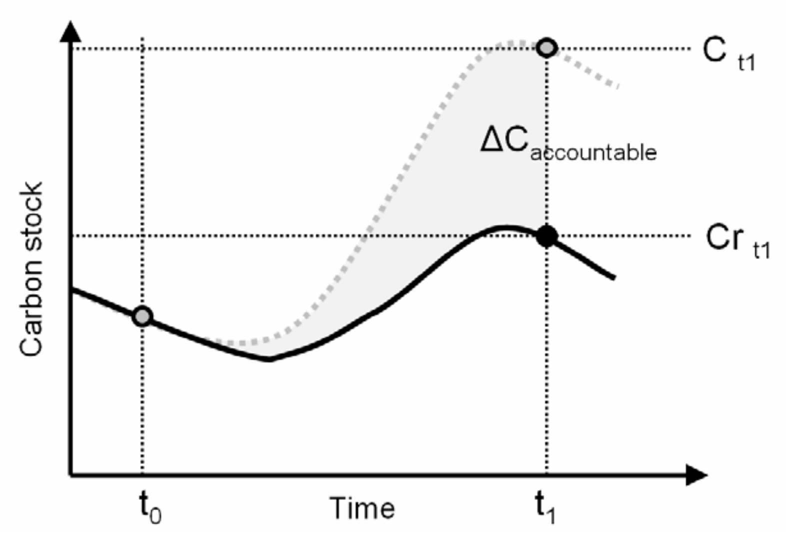


Figure 25: Dynamic baseline concept to account for a change in management. A reference scenario (e.g. Business as Usual, black line) as described by a forestry model is compared against a management change scenario (grey dotted line). Both scenarios start from the observed conditions.

A dynamic baseline to factor out age-class effects

The approaches so far neglected the dynamic nature of C sinks and sources in forests due to their age-class distribution or excluded it. A variation of the dynamic baseline concept is displayed in Figure 26 that allows quantifying the legacy effect. The legacy effect of a forest landscape can be determined with a comparison of two scenarios that follow the same management or disturbance rules but start from two different starting points. One represents the observed conditions of the forest landscape; the other assumes ideal conditions of a reference landscape. Relative changes in carbon stocks occur only due to differences in the initial age-class structure. At some point in time the legacy effect might elapse (black and grey solid lines merge). Depending on the complexity of the landscape and age-class structure, this point may lie many decades in the future. Figure 26 clearly shows that the effect of age-class distribution is additional to changes in management.

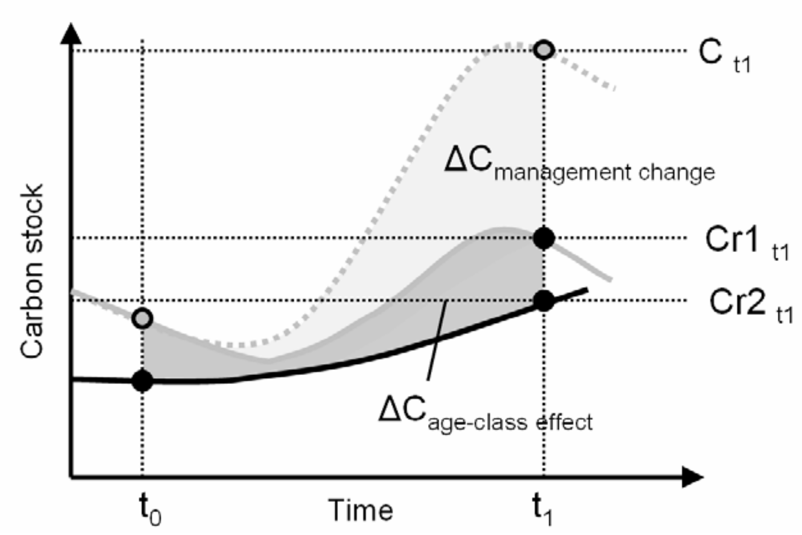


Figure 26: Dynamic baseline concept with two applications: 1) to account for a change in management and 2) accounting against a reference age-class structure. Dotted grey line and solid grey line have the same starting point but consider different management, the difference between solid grey and black line is the initial age-class structure. The difference between the latter is the carbon stock change due to the age-class legacy effect.

FIVE.5 Discussion

The current situation, whether a forest region is a source or a sink, as well as the future development and also the effect of management change measures are very much depending on the age-class structure of the respective region. The age-class structure itself is a product of past practices. The disturbance history of a forest landscape has different implications on the future carbon balance depending on the future disturbance. It is not deterministic. To fulfill the Marrakesh Accords the parties not only need to look back but also need to look into the future.

Table 18 summarizes the presented approaches and discussion. 'Gross-net' accounting reflects the atmospheric signature but includes stock changes due to past practices and offers therefore no incentives for countries where these effects are large and leading to declining stocks. 'Net-net' looks at changes in C stock change rates. Still, age-class effects are included but incentives switch side because slowing C stock decline is awarded and diminishing increase punished. Approaches that are based on average age or average carbon stocks neglect or only partly exclude age-class effects. The result is that their climate effectiveness is relatively low because accountable stock changes are not directly related to removals from the atmosphere. A dynamic prospective baseline creates incentive for change in behavior even in cases in which the baseline indicates a declining C stock and reduces 'windfall' credits where business as usual indicates increasing C stocks. The approach also offers ex-post adjustments to the baseline once the actual natural disturbance or business as usual is known.

A dynamic baseline application to a reference age-class structure can quantify effects of age-class legacy. These findings could be incorporated in a more sophisticated accounting. A dynamic baseline approach can be a valid concept to build an effective carbon accounting on. Compared to fixed reference points, a baseline can be used to capture effects that change over time. It integrates over an entire landscape and comes thus closest to observable stock changes for validation.

The question, whether such an accounting would create more incentives for any party and who 'wins' and who 'loses' depends on the reference scenario chosen. Chapter Six will address this question for European countries and assess the proposed accounting approaches on a quantitative basis.

Table 18: Overview of presented approaches and their performance under evaluation criteria. Incentives are split to parties of two types: countries with left shifted (LS) age-class structure that will probably face increasing stocks in the future due to age-class effects and countries with decreasing stocks due to a right shifted (RS) age-class structure (see model exercise above).

Approach	Closeness to atmospheric signal	Effect of age-classes	Incentives for opting for accounting		Applicability and validation
			LS	RS	
Gross-net	closest	included	high	low	simple
Net-net	close	included	low	high	simple
Reference: Average Carbon Stocks	far	neglected	medium	medium	theoretic
Reference: Average Age	far	partly excl.	low	high	theoretic
Reference: Business as usual	close	excluded	high	high	medium complexity
Reference age-class structure	far	quantified	depends on reference		complex

As stated earlier: the challenge of the implementation of a baseline is not the generation of the reference level. Forestry models like the one applied here are capable of reflecting all effects associated with age-class structure or past practice. More complex models require more parameters and a sound initialization of pools. Data intensity might be a serious shortcoming of complex approaches. However, more problematic is the definition of the reference case to choose. Disturbance and management regimes in reality are hardly constant over time. The concept of an ideal managed or the perfect negative exponential distribution in a fire dominated system are more theoretical but hardly observed because forest landscape is usually formed through various kinds of disturbances.

Finding the best definition of a baseline is a challenge. It has to serve various purposes: providing incentives for opting for such an accounting, being climate effective, and allow for an independent validation.

All baseline approaches to carbon accounting bear the danger of a certain form of leakage. The IPCC Special Report on LULUCF defines leakage in Section 5.3.3. as an *"unanticipated decrease or increase in GHG benefits outside of the project's accounting boundary […] as a result of project activities."* This definition targets at carbon emissions caused by the accounted activity but occurring outside the accounting area (e.g. deforestation outside a conservation area). Leakage through baseline definition on the other hand occurs by an inappropriate baseline definition. For example, the definition of a baseline on the coverage of a forest management activity that is far beyond technical feasibility. This type of leakage is also true for the definition of deforestation baselines. Unrealistic high rates of deforestation that are unlikely to occur might give carbon credits to parties for continued deforestation slightly under the defined baseline. The largest problem associated with baselines is their establishment in a credible way.

So far the forest inventories reported to IPCC and used as a basis for accounting implicitly include natural disturbances. The age structure recorded in these inventories can be interpreted as a memory of past stand replacing disturbances. The Marrakesh Accords mention only the effect of 'activities'. A close interpretation would lead to an exclusion of effects that natural disturbances like windfalls and fire could have on the age-class structure. This interpretation would not allow the accounting of age structure effects in many regions that have been taken under management only in the last past decades and where natural disturbances are the largest contributor to the age-class structure that can be observed there today. A discussion of this issue is beyond the scope of this chapter.

SIX

QUANTIFICATION OF CLIMATE CHANGE MITIGATION POTENTIAL AND ACCOUNTING OF FOREST MANAGEMENT IN EUROPEAN COUNTRIES

SIX.1 Introduction

The previous chapter emphasized how past practices influence the climate change mitigation potential of managed forests and which mechanisms have to be accounted for, when future projections are made. This chapter of the thesis uses the forestry model FORMICA to quantify the mitigation potential of forest management in European countries over a period of 60 years. The scope of the chapter is twofold: First, the future of forestry related C stocks under prescribed management scenarios is studied. Second, this part of the thesis focuses on how to quantitatively factor out past forest conditions and how to separate out impacts of changes in forest management against a baseline. Effects of choices of accounting rules applied to real data show 'winners and losers' of different accounting schemes. Information to answer the question under what national circumstances countries will profit more or less from a specific accounting rule is needed and will affect the scope for political negotiations.

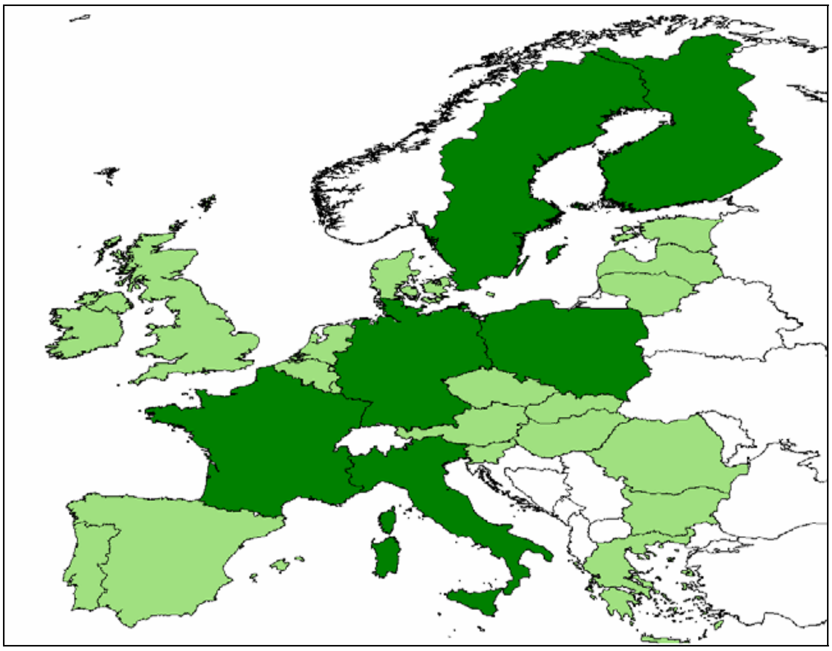


Figure 27: Map of countries considered in quantification of mitigation potential. Dark green countries are looked at in detail, dark green and light green countries are examined as EU27. Of the 27 EU member states only Malta and Cyprus are not covered in this analysis. Nevertheless in the following it will be referred to EU27 to stress that the group contains Romania and Bulgaria.

SIX.2 Materials and methods

The quantitative analysis takes 27 European countries (EU27) belonging to the European Union into consideration. However, the analysis will focus on some countries with particular characteristics.

Table 19 gives a summary of basic features of selected countries. A summary of the age-class distribution in these countries is given in Figure 29. Since 1950, the European forest area has not decreased in any EU member state (National Communication EU, 2001; National Communication EU, 2006). A shift towards young forests for some countries indicates that large parts of the forest are still regenerating after intensive exploitation decreased. This is true especially for Italy and Poland. In the course of the last 50 years forest area in Italy increased by 75%. In Finland, comparably old forests exist (compared to the currently applied management) while in Western European countries forest structure is more complex. In a special situation is Slovenia, where forests are comparably old and age-class structure is shifted to the right.

Table 19: Selected countries and their decision on Article 3.4 Forest Management, limits for accounting net removals for Forest Management under Article 3.4, basic, qualitative description of current age-class distribution and forest area in 2005 (FAO, 2005).

Country	3.4 FM elected?	Cap [Mt C yr^{-1}]	Age-class structure description	Considered forest area [1000 ha]
Finland	yes	0.16	Maximum area at age 30, average age = 55, 50% younger than 60, 7% older than 160	22 500
France	yes	0.88	Maximum area at age 30, average age = 54, 50% younger than 45, 1% older than 160	15 554
Germany	yes	1.24	Maximum area at age 30, average age = 54, 50% younger than 50, 1% older than 160	11 076
Italy	yes	20.78	Maximum area at age 10, average age = 36, 50% younger than 20, 0% older than 160	9 979
Poland	yes	0.82	Maximum area at age 30, average age = 52, 50% younger than 40, 0% older than 160	3 783
Slovenia	yes	0.36	Maximum area at age 90, average age = 84, 50% younger than 80, 0% older than 160	1 264
Sweden	yes	0.58	Maximum area at age 10, average age = 61, 50% younger than 60, 0% older than 160	27 528
EU27	-	-	Maximum area at age 30, average age = 48, 50% younger than 50, 2% older than 160	121 201

SIX.2.1 Description of datasets and model initialization

The forestry model FORMICA (Böttcher et al., in press) projects the development of forest biomass carbon (above and below ground). The model uses data from forest yield tables to describe forest growth. We used a collection of European yield tables (Federici et al., 2001) to parameterize forest growth of single forest types.

Allocation from stem volume to total biomass was done through a simple global relationship (Enquist and Niklas, 2002). Conversion of total volume to total biomass was done with IPCC Good Practice Guidance LULUCF default values for wood densities (IPCC, 2003b). Carbon content was considered to be constant over all species and compartments and set to 0.5. The simulations cover the period of 50 years. This period is relatively short for forest management but covers the period which is relevant for climate change mitigation policies. In addition, it is not yet too affected by climate change, which is beyond the scope of this study.

Basic information on age-class distribution for the analysis was derived from the European Forest Resource Database (EFRD), which has been established as an extension of European Forest Institute (EFI) Forest Scenario Modeling Project (Schelhaas et al., 1999). The data cover 34 European countries and are a compilation of national forest inventories. For a number of countries, the dataset relies on data from the IIASA Forest Study (Nilsson et al., 1992). The average reference year of the dataset is 1990.

The species-specific data on age-class areas from EFRD were aggregated on three levels to forest management types. Four geographical eco-regions were defined: boreal, central, east and south. Within the regions, the data were split into three forest types: broadleaved trees, conifers and mixed forests. These groups again were divided into three management classes: long- and short-rotation systems according to the oldest age-classes found and an unmanaged group. A combination of these strata resulted in 28 forest types that are represented differently in the considered countries (Table 20).

The emphasis in this study is on the status of forest biomass and forest age-class distribution since this information is most relevant to trace legacy effects of past disturbances and management. Soil and litter pools and carbon stored in harvested wood products are included to cover the direct mitigation potential of the entire forestry sector.

Table 20: Detailed overview of selected countries of percent of total country forest area in different strata, i.e. eco-region, species group and management type per age-class.

Country	Strata	Rotation	Percentage of total area per age-class								
		[years]	10	30	50	70	90	110	130	150	>160
Finland	Boreal, broadleaved, long	80	0.9	3.1	2.1	1.3	0.6	0.2	0.1	0.1	0.0
	Boreal, coniferous, long	80	14.9	14.8	14.6	15.4	11.8	6.8	4.2	2.5	6.7
France	Central, broadleaved, long	120	7.0	11.5	11.8	7.4	5.6	3.6	3.5	3.0	1.4
	Central, coniferous, long	100	11.9	12.8	8.1	4.5	3.0	1.7	1.2	0.9	1.1
Germany	Central, broadleaved, long	120	4.4	5.8	5.4	4.5	4.5	3.7	3.0	1.8	1.0
	Central, coniferous, long	100	10.0	16.5	11.4	11.9	9.2	4.5	1.8	0.6	0.2
Italy	Central, broadleaved, long	120	0.3	0.6	0.9	0.8	0.6	0.4	0.2	0.1	0.0
	Central, broadleaved, short	100	1.9	7.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Central, coniferous, long	100	0.6	0.7	0.9	0.9	0.8	0.7	0.6	0.5	0.0
	South, broadleaved, long	80	2.7	1.7	1.0	0.6	0.4	0.3	0.1	0.0	0.0
	South, broadleaved, short	60	34.1	29.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	South, coniferous, long	80	2.8	2.1	1.4	1.0	0.7	0.5	0.3	0.2	0.0
	South, coniferous, short	60	0.9	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Poland	Central, broadleaved, long	120	4.0	6.1	4.5	2.8	1.8	0.9	0.7	0.0	0.0
	Central, coniferous, long	100	19.0	19.4	17.1	12.6	7.9	2.3	1.1	0.0	0.0
Slovenia	Central, broadleaved, long	120	1.8	0.8	7.9	14.1	15.8	8.6	3.9	1.7	0.0
	Central, coniferous, long	100	1.8	2.1	5.8	9.9	11.8	7.5	3.8	2.8	0.0
Sweden	Boreal, broadleaved, long	80	0.4	1.0	0.8	0.6	0.3	0.2	0.2	0.1	0.0
	Boreal, broadleaved, short	60	0.6	1.6	1.5	1.0	0.4	0.2	0.0	0.0	0.0
	Boreal, coniferous, long	80	11.0	6.5	3.7	4.6	5.3	6.2	4.9	3.8	0.0
	Boreal, coniferous, short	40	11.5	7.9	5.6	7.4	6.4	3.7	2.5	0.0	0.0

The initialization of the biomass pools was derived from an upstream model run. This model run simulates forest growth and management under conditions that lead to biomass stocks in the strata that match the global inventory values at the regional level. Initialization of models often causes artificial changes in variables that are due to an imbalance of state variables in the first simulation periods. To exclude such effects also initialization of soil and litter and product pools was done through model spin-up runs.

The soil model Yasso (Liski et al., 2005) included in FORMICA simulates the stock of soil carbon, changes in this stock and the release of carbon from soil on an annual basis. It needs estimates of litter production, information on litter quality and basic data on climate to run (Liski et al., 2005). Climate parameters required by the model are mean temperature (T), sum of precipitation (Prcp) and sum of potential evapotranspiration (PET) during growing season. Climate parameters for the European region were derived from the European Centre for Medium-Range Weather Forecasts (ECMWF) data reanalysis (ERA-40) which is based on meteorological observations from September 1957 to August 2002 (Uppala et al., 2005).

SIX.2.2 Management scenario description

Table 21 lists the scenarios that have been considered. Besides a Business as Usual run that describes the expected development of sources and sinks under continued application of the current management, there are two scenarios that focus on the initial condition of the age-class structure that is underlying (Normal Forest and natural forest). Two other scenarios are used to point out implications for the regional carbon budget when a management change is taking place: lengthening and shortening of rotations.

Table 21: Scenarios of forest management and management change applied in this study.

Scenario	Difference to BaU	Description
Business as Usual (BaU)	-	Continued classical management starting from the observed age-class structure
Longer rotation (LONGER)	Management	Increased rotation length by 20% of all forest types starting from the observed age-class structure
Shorter rotation (SHORTER)	Management	Decreased rotation length by 20% of all forest types starting from the observed age-class structure
Normal Forest (NF)	Age-classes	Uniform age-class distribution is considered, i.e. every age-class has the same area
Natural forest (NatF)	Age-classes	An class distribution is considered that is typical for naturally disturbed forests

Business as Usual

The management of a forest region in the Business as Usual (BaU) scenario is considered an ideal management, ignoring large-scale disturbances or changes in market conditions. Rotation length is derived from national recommendations for certain forest types or estimated from the forest inventory.

To avoid too deterministic carbon fluxes, simply following the age-class structure of a forest region and being thus very uneven, a tool for regulated harvest levels was implemented (see Chapter Two description of FORMICA regional module). Each period, the forestry model determines the periodical allowable area of mature forest to be cut and thus ensures sustainable forest management. Both criteria, forest age >= harvest age and harvested area <= periodical allowable harvest area, lead to a constant harvest volume flow, assuming no market shifts and no increase in the demand of wood products. The assumption of a fixed market is the most reasonable assumption for model simulations without integrated economic feed back loops.

Longer rotation

The scenario of longer rotations accounts for the often proposed contribution of the forestry sector to the CO_2 mitigation by letting trees getting older. By reducing harvest rates, compared to Business as Usual this measure could lead to an increase in forest biomass stocks and remove CO_2 from the atmosphere.

The effect on the carbon balance of this scenario is considered to demonstrate the technological-biological potential, rather than as a realistic management option. How effectively this measure will be implemented in the future is to a large degree dependent on economic incentives. Due to economic reasons rotations might be prolonged without additional incentives for C storage. If prices for large dimensional timber are low, forest owners tend to keep high growing stocks. To predict for which forest types and which regions rotation length enhancement could be a viable option is difficult. This study prescribes a general prolongation of rotations by 20% for all regions and forest types.

Shorter rotation

The rotation time in managed forests is determined by the potential product the forest owner wants to sell. The demand for a certain quality, quantity and type of product is changing over time and also linked to the technological development of wood processing. European pulp and paper demand during the last decades increased more rapidly compared to the demand of sawn timber (UNECE, 2005). Over the next 20 years, it is expected that renewable energy policies encourage the establishment of short-rotation forest plantations for wood fuel production (UNECE, 2005). In addition there is a trend towards compound products, resulting in a higher demand for sawn timber of smaller diameters. It is likely that economic conditions will favor a reduction of rotation time in the future in some forest management regions. A scenario of 20% shorter rotations in all forest regions is estimating implications for forest biomass carbon if the average age of timber production forests would be reduced.

The management change in both scenarios is not applied immediately for the entire target area but spans over a period of 40 years.

SIX.2.3 Age-class scenario description

Findings from Chapter Five emphasized the importance of past practices and the resulting age-class structure for recent and future C dynamics. The impact of forest management and management change as a mitigation measure also depends on these initial conditions. To quantify effects of age-class structure, two scenarios of artificial age-class distribution are calculated with manipulated starting points (Figure 28). All three management scenarios (BaU, LONGER and SHORTER) were applied to the different landscapes.

Normal Forest

The simplest age-class distribution is the one of an undisturbed ideal plantation landscape. It is ideal with respect to continuous sustainable timber flow but can hardly be observed under real conditions, where wars, market breakdowns, natural disturbance etc. cause irregular harvests or other losses. The forestry model applied here neglects economic feed backs on timber harvests and considers a continuous demand for products in the Business as Usual scenario.

The Normal Forest (NF) landscape is only controlled by management, i.e. by the rotation length applied. If management changes (e.g. the rotation is shortened) the ideal age structure changes as well because the forest area will then be distributed to fewer age-classes. If all initial stocks at the stand level are in equilibrium and if management does not change, this scenario would let C stocks neither increase nor decrease. How the initial age-class structure deviates from Normal Forest structure can be observed in Figure 29.

Natural disturbance

Although forests in Europe are to a very large degree intensively managed, natural disturbances cannot be excluded from them. Schelhaas et al., 2003 estimated from a literature review that between 1950 and 2000 storms caused 53% of the total damage (in wood volume of annually 35 million m^3), fire was responsible for 16%, and biotic factors caused 16% of the damage (half of this was caused by bark beetles). More than 90% of the forest area that burned per year was located in southern Europe, France and Turkey. Most of the damage from storms was reported in Central and Western Europe, especially in mountainous areas. Damage through biotic factors (like beetles) was less clearly distributed but to some extent correlated with storm damages that predispose forests to insect outbreaks.

To better reflect the individual situation of countries, the reference age-class structure (NatF) should take these past disturbances into account. We assumed three basic disturbances to be dominating in Europe, storm, fire, and biotic, leading to different age-class distributions if they are considered to be constant (Figure 28). Forest type specific disturbance regimes were derived from literature data and the Database on Forest Disturbances in Europe (DFDE, Schelhaas et al., 2001) on forest disturbance rates and frequencies for fire (Gromtsev, 2002; Kuuluvainen et al., 2002; Pennanen, 2002; Uotila et al., 2002), storm (Holmsgaard, 1986; Pontailler et al., 1997; Lässig and Mocalov, 2000). Resulting disturbance groups were attributed to the forest management strata mentioned above and aggregated on country level (Figure 30). The aim was not to reflect a realistic, individual situation of each country but to provide an alternative, natural-disturbance based reference scenario to the management based reference scenario of NORMAL forest.

Different age-class distributions result in different age-class weighted average ages for the selected countries (Figure 31). Compared to average age calculated from the observed age-class structure, average age increases for France, Italy and Poland if a Normal Forest structure is considered. In all other countries forests would be younger under these conditions. The reference age-class structure that represents a landscape dominated by natural disturbances leads to an increase in average age for almost all countries except Slovenia and Sweden. The observed average age of Finland and Sweden is closer to values of average age if natural disturbance is the reference and not plantation. For France and Germany difference in average age between the two concepts and observed values are relatively small.

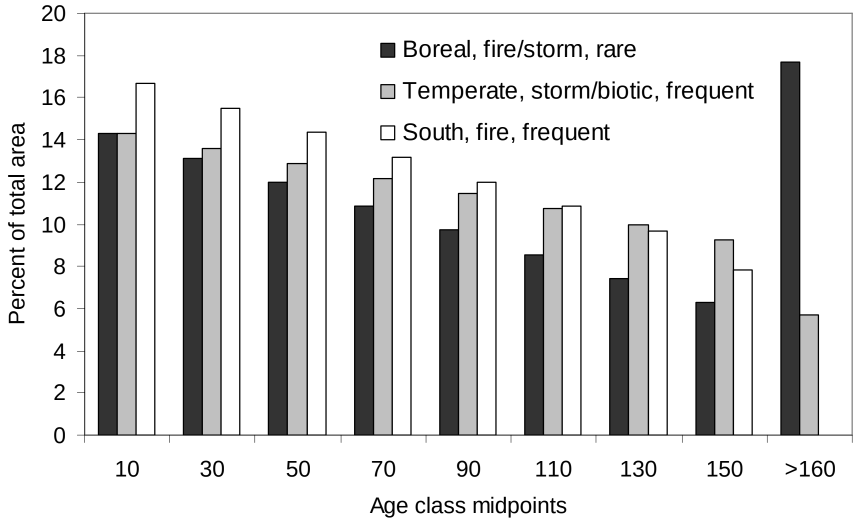


Figure 28: Reference basic age-class structures considered as 'natural' distributions.

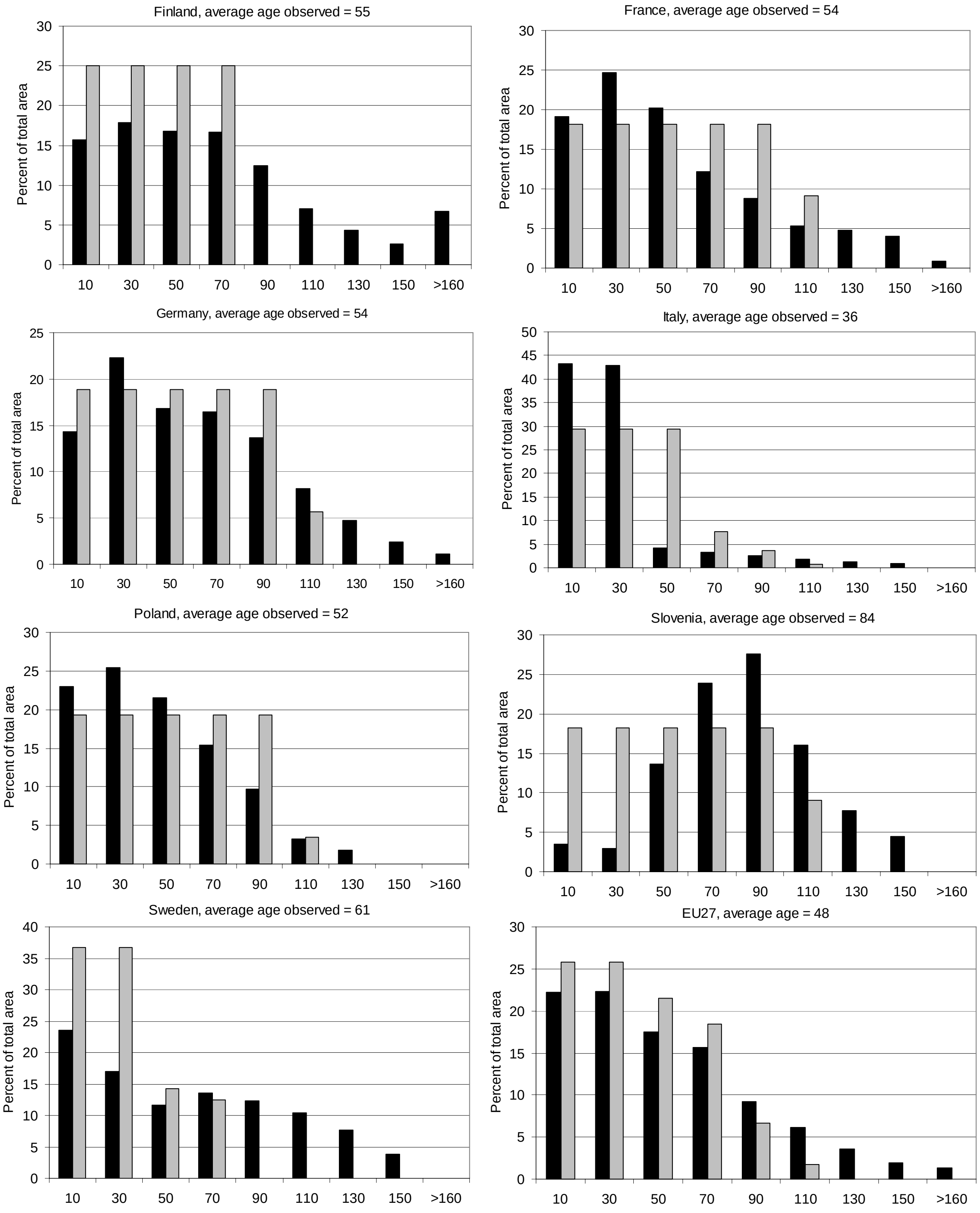
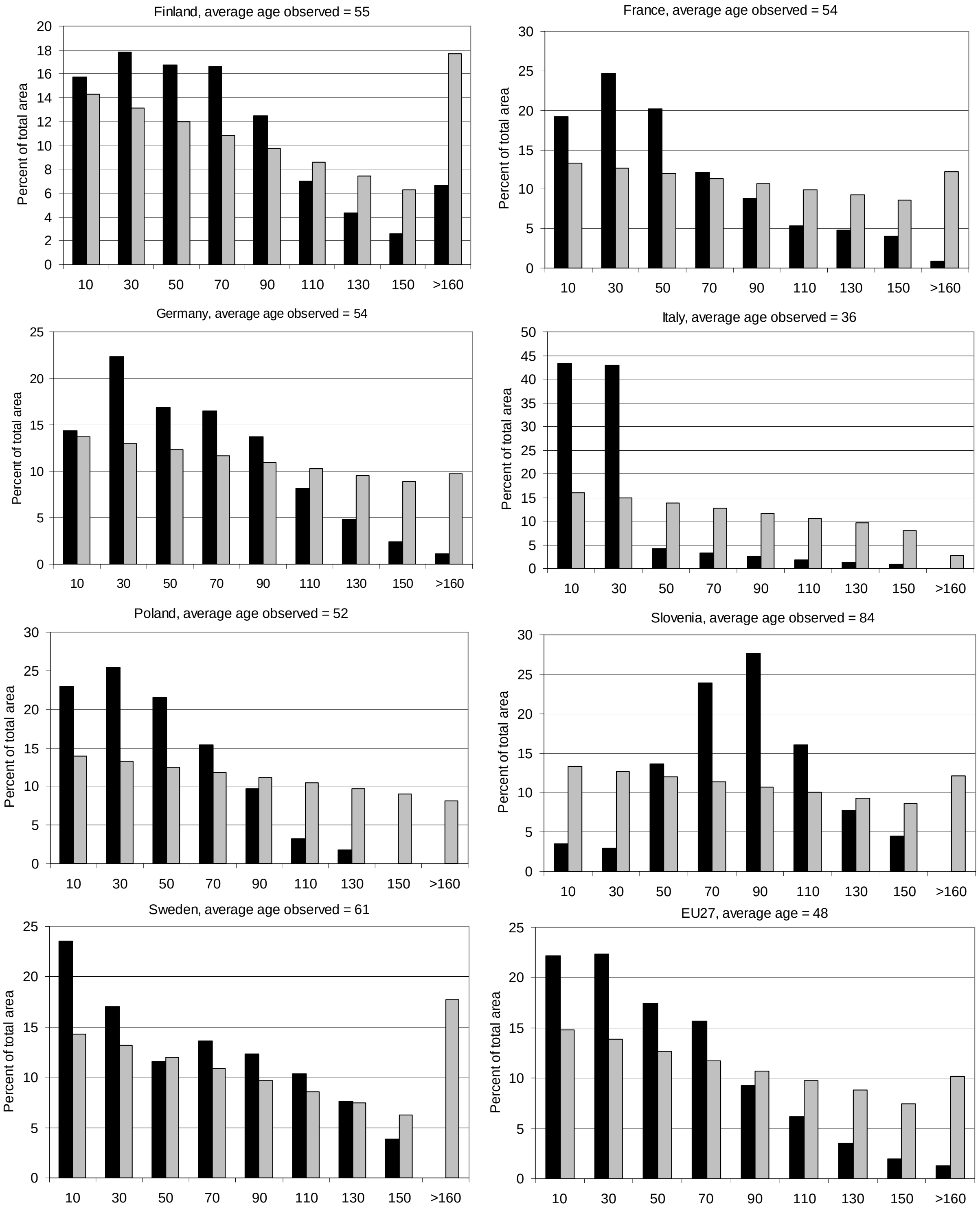


Figure 29: Comparison of observed relative age-class distribution (black bars) to a reference Normal Forest structure for Finland, France, Germany, Italy, Poland, Slovenia, Sweden and the group of EU27. X-axes show age-class midpoints in years.



Finland, average age observed = 55

France, average age observed = 54

Germany, average age observed = 54

Italy, average age observed = 36

Poland, average age observed = 52

Slovenia, average age observed = 84

Sweden, average age observed = 61

EU27, average age = 48

Figure 30: Comparison of observed age-class distribution (black bars) to a reference naturally disturbed forest structure for Finland, France, Germany, Italy, Poland, Slovenia, Sweden and the group of EU27. X-axes show age-class midpoints in years.

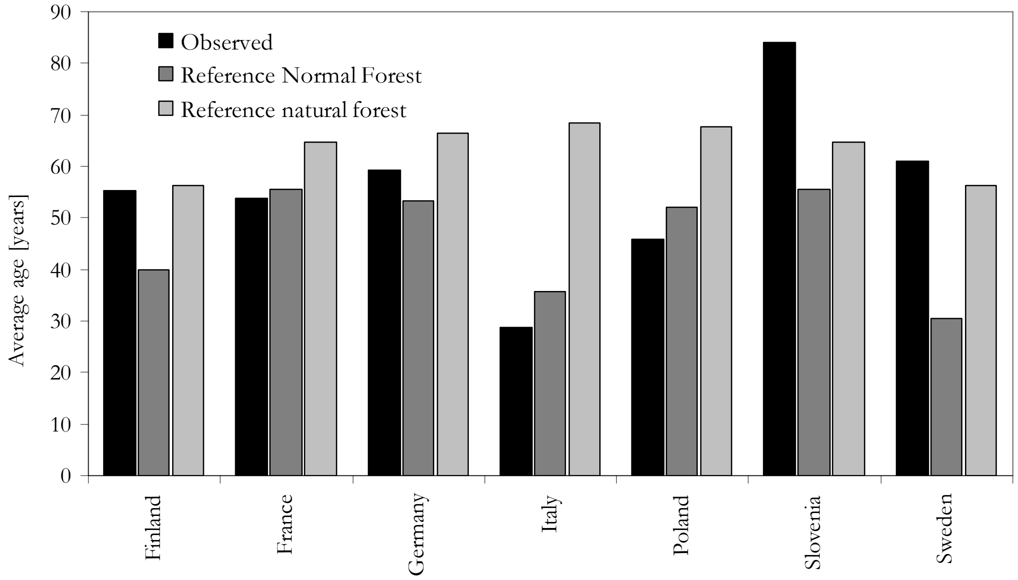


Figure 31: Average age of forest landscape at the start of the simulation in different countries and for different initial age-class distributions.

SIX.3 Results and discussion

SIX.3.1 C stock changes and effects of management change

The carbon stock change in forest biomass in different countries varies with climatic, past and recent management conditions. Figure 32 shows the development of biomass C fluxes of the seven selected countries. Countries with relatively large portions of old forests, which is reflected in a higher average age compared to the respective Normal Forest value (cf. Figure 31) are currently losing carbon (Finland, Sweden and Slovenia). Others gain with a diminishing trend due to aging. Around year 2040 emissions and removals from all countries are close to zero.

According to the model, within the group of EU27 around 20 Mt C could be stored in forest biomass, soil, litter and harvested wood products annually over the next decade. The sink is very likely to get smaller throughout the next 30 years due to forest aging by a rate of about 1 Mt C per year (Figure 33). A prolongation of rotations by 20% can prevent the sink from diminishing for at least a period of 40 years. Compared to Business as Usual the forestry sector in Europe could store more than 800 Mt of C additionally until 2050 if rotation lengthening would be extensively applied. In the likely case that rotation periods shorten, the sink will have approached zero already by 2025, switching into a source thereafter. In 2050 the emissions from forest management will have already compensated the increase that occurred between 2000 and 2020.

A change in rotation length is associated with a change in harvest yields and flow of C from biomass to harvested wood products. Figure 34 describes changes in biomass and forestry sector C stocks due to management change for the EU27 group compared to Business as Usual. Inclusion of products and soil and litter C compensates partly for losses or gains in biomass C associated with change of rotation length. The degree of compensation depends on efficiency of product processing, wood product use and efficiency of fossil fuel substitution. The latter is not considered in these simulations due to lack of sufficient data. Results of Chapter Three indicate a large potential of fossil fuel substitution for timber oriented forestry if recycling rates are high and wood product waste is incinerated for secondary bioenergy production.

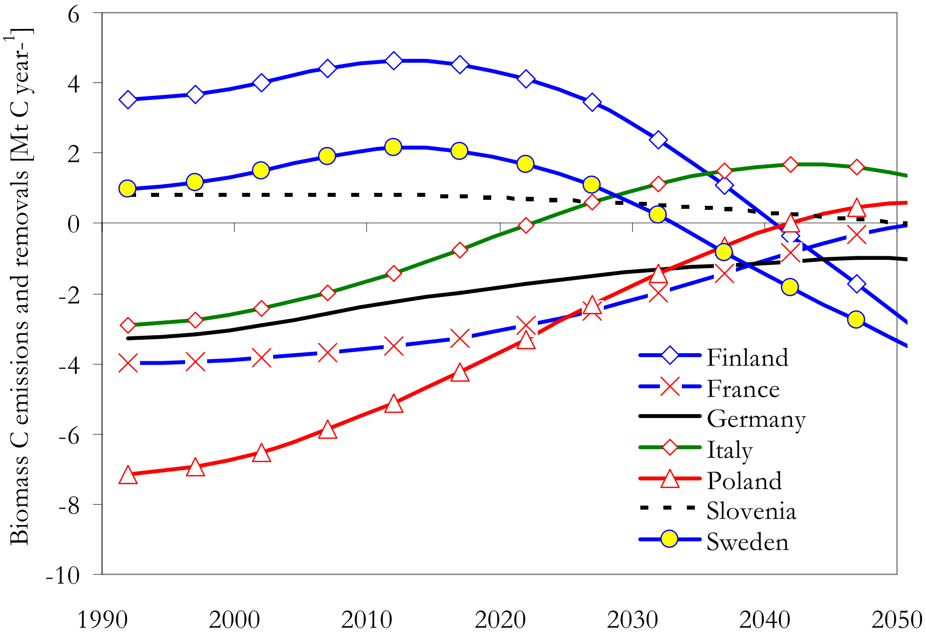


Figure 32: Development of forest biomass C sinks and sources under Business as Usual in selected countries as projected by the model over 60 years simulation period. Emissions have positive sign, removals negative.

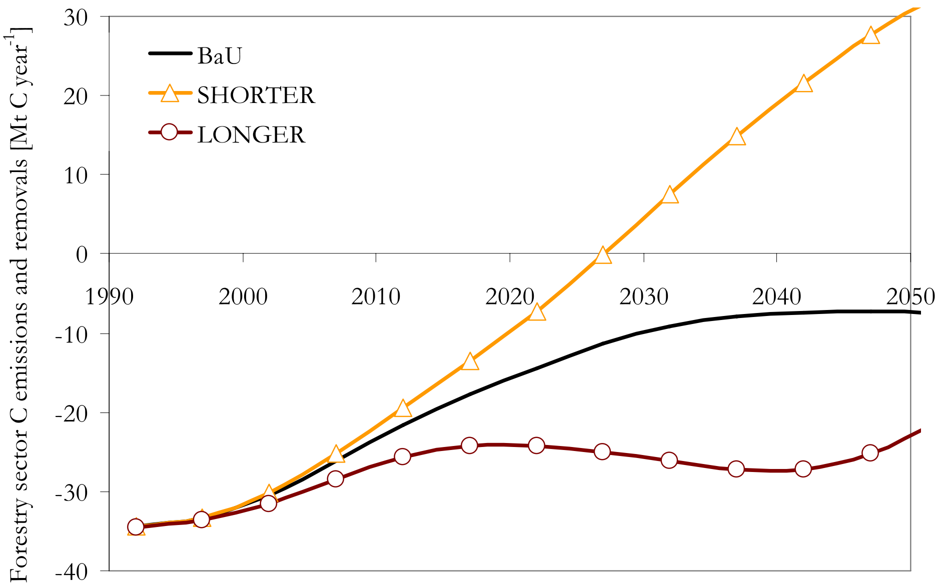


Figure 33: Development of the forestry sector C sink (ecosystem plus harvested wood products) over 60 years simulation period for the EU27 group. Emissions have positive sign, removals negative.

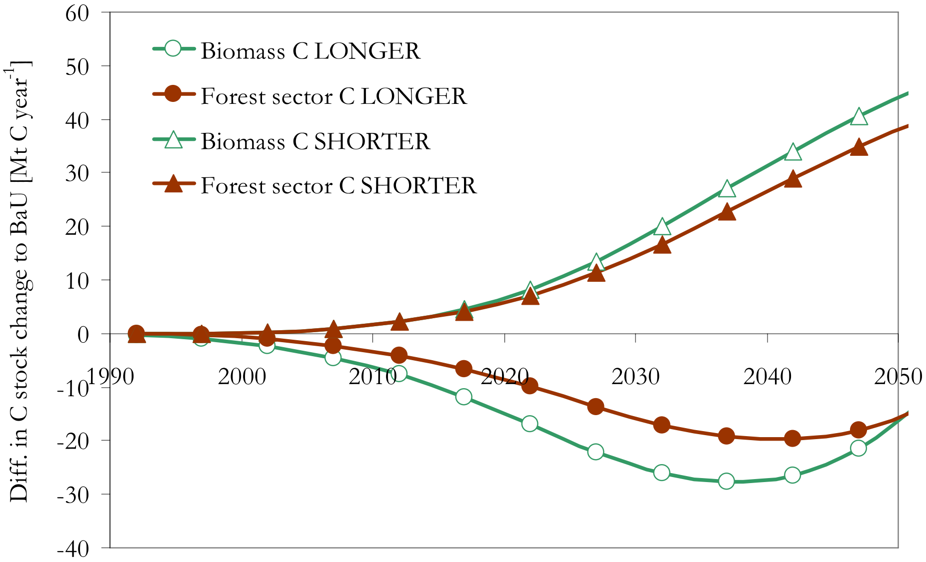


Figure 34: Differences in C stock change for EU27 in the SHORTER and LONGER scenario compared to BaU for biomass and forest sector C. Inclusion of products and soil and litter C compensates partly for losses or gains in biomass C associated with change of rotation length.

SIX.3.2 Accounting of management change

Chapter Five discusses various ways of accounting through choosing different references (see Table 18 there). Table 22 summarizes the implications for accountable sources and sinks in the second commitment period (2013-2017) of a specific baseline definition. The values describe average emissions and removals in tonnes per ha and year to allow for comparison between countries. Numbers 2) – 4) describe the sink or source under scenarios as it is observed during the commitment period ('gross-net'). If accounting rules and cap of the first commitment period would be applied to an accounting in the second commitment period, the accountable amount would be truncated at 10). Countries with old forests (Finland, Sweden and Slovenia) would have debits from forest management even if rotations would be lengthened. However, on average EU27 countries would benefit from 'gross-net' accounting because of age-class structure and current management.

Accounting against stock changes in a base year (e.g. 1990, 'net-net') is shown with 5) – 7). If Finland continues Business as Usual (5)) it would increase emissions from forest management compared to 1990 and receive a debit. So do nearly all other countries (except Slovenia) but for different reasons. Some countries (e.g. Germany, Italy and Poland) that benefit through increasing biomass stocks from 'gross-net' loose with 'net-net' due to a slower increase between 2013 and 2017 compared to 1990. Some countries (Finland and Sweden) receive credits if harvest is delayed with longer rotations but most can simply lower their debits.

A third accounting approach is applied in 8) and 9). The stock changes in scenarios LONGER and SHORTER are compared with the development under Business as Usual for the same period of time. Including such a reference baseline clearly distinguishes effects of management change. A change in management towards longer rotations would create credits for all selected countries and the group EU27. Despite decreasing C stocks in biomass (2)) Finland can account for credits from rotation lengthening. However, these accounted amounts would be considerably smaller compared to 'gross-net' and in most countries hardly exceed the respective cap. The comparison of the observed C stock changes against a baseline scenario is therefore necessary to give incentives for effective mitigation measures.

Table 22: Comparison of accountable biomass emissions (positive sign) and removals (negative sign) from forest management according to different accounting methods in the second commitment period 2013-2017 in t C per ha and year. *) EU27 does not have an assigned cap; this is the sum of caps assigned to EU27 member states.

	Scenario/ Accounting	Finland	France	Germany	Italy	Poland	Slovenia	Sweden	EU27
1)	BaU 1990	0.16	-0.26	-0.30	-0.29	-0.77	0.72	0.04	-0.20
2)	BaU 2013-2017 'gross-net'	0.21	-0.22	-0.20	-0.11	-0.50	0.69	0.08	-0.08
3)	LONGER 2013-2017 gross-net'	0.14	-0.26	-0.28	-0.16	-0.59	0.59	0.03	-0.15
4)	SHORTER 2013-2017 'gross-net'	0.22	-0.20	-0.13	-0.13	-0.41	0.61	0.07	-0.05
5)	2)-1) BaU 'net-net'	0.05	0.04	0.11	0.18	0.27	-0.03	0.04	0.13
6)	3)-1) LONGER 'net-net'	-0.02	0.00	0.02	0.13	0.17	-0.13	-0.01	0.06
7)	4)-1) SHORTER 'net-net'	0.06	0.06	0.18	0.16	0.36	-0.10	0.03	0.15
8)	3)-2) LONGER against baseline BaU	-0.07	-0.04	-0.08	-0.06	-0.09	-0.10	-0.05	-0.07
9)	4)-2) SHORTER against baseline BaU	0.01	0.02	0.07	-0.03	0.09	-0.07	-0.01	0.03
10)	Cap	0.03	0.21	0.03	0.07	0.32	1.19	0.08	* 0.26

SIX.3.3 Effects of past management

The age-class structure at the beginning of the simulation influences the projection of carbon stocks. All pools were initialized by model spin-up to achieve equilibrium conditions of variables in the beginning of the simulation. The only variable that was not balanced was the age-class structure. In this setup, modeled stock changes occur only due to the age-class legacy (cf. Figure 32). According to these assumptions any stock change observed under the modeled continued Business as Usual scenario can be considered to be an effect of past practices.

A comparison of the simulation results reveals differences between scenarios for management change with different underlying age-class distribution. Two sets of scenarios comprised model runs with manipulated age-class distributions. These are contrasted with results of runs with inventory derived distributions. Figure 35 shows the comparison of biomass carbon stock changes in a scenario of rotation shortening for different countries and initial conditions. It presents the effect of age-class distribution on management change. This is expressed in magnitude of relative stock change and timing. Because of a shift of its age-class structure towards older forests in Finland, emissions from rotation shortening from biomass (assuming no retain by products and soils) are delayed in comparison to a Normal Forest and natural forest age-class structure. A long 'tail' of old forests far beyond rotation time as simulated in the natural forest age-class scenario leads to earlier emissions. In the case of France there is practically no difference in emissions between observed and Normal Forest age-class structure.

The exercise of simulations with different initial age-class distributions shows that there are past practice effects that occur with management change. Timing matters for climate change mitigation through forest management. The same management applied to different regions leads to different results, but since time changes age-class structure, this applies also for different points in time in the same region.

In the long run, if considering that forest regions are managed in the same way, the age-class effects are diminishing over time, i.e. it converges towards zero. This is because a model assumption is that the forest land is managed in a way that leads towards an evenly distributed age-class structure to ensure continuous future timber flow and ignoring natural disturbances or market breakdowns. Forest planning is usually aiming at such a forest age structure, however, the market situations and extreme conditions are very likely to counteract these plans.

While management change can only emphasize or abate the strength of sink or source, age-class structure drives the direction of stock changes for a long period of time. This has to be considered when a baseline for accounting is established.

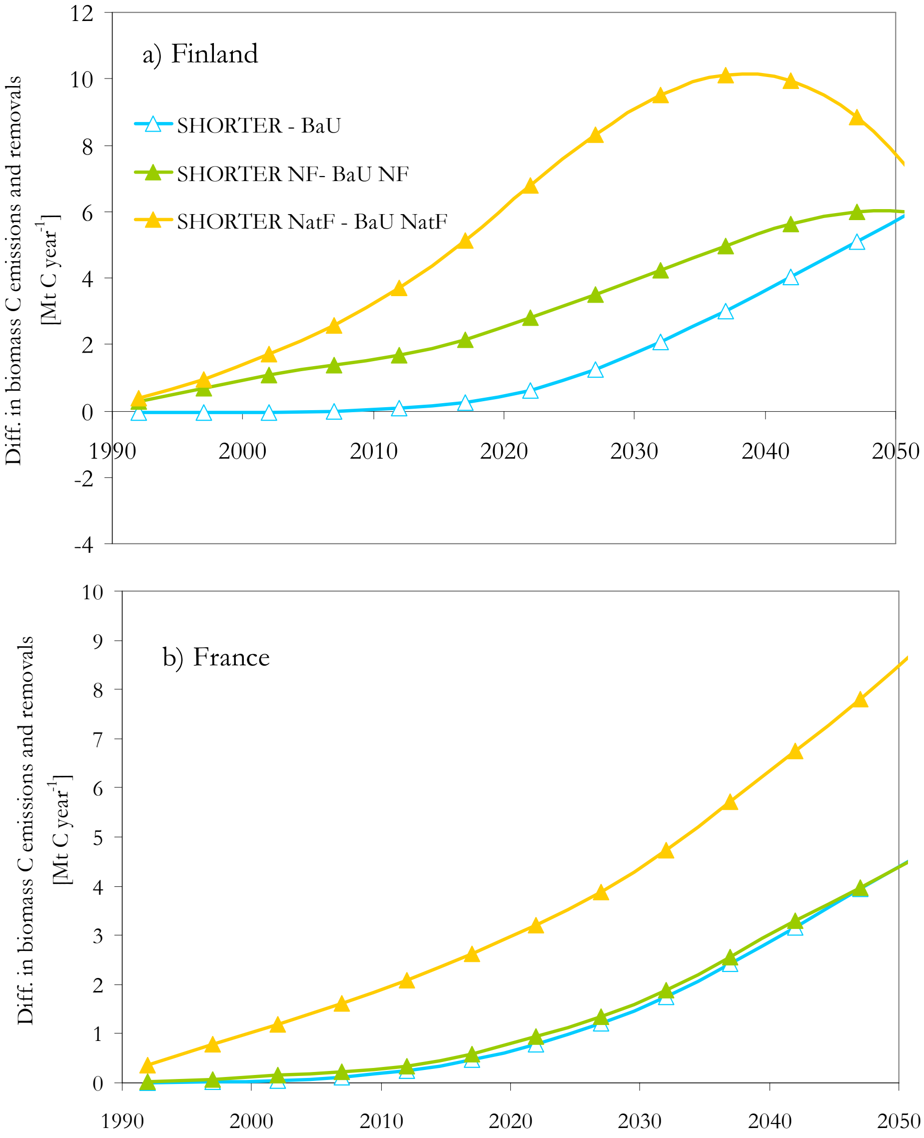


Figure 35: Comparison of biomass C stock change in the SHORTER scenario compared to Business as Usual applied to different initial age-class distributions for a) Finland and b) France. NF = Normal Forest age-class structure is underlying, NatF = natural forest age-class is reference.

SIX.3.4 Accounting of past practices

The accounting against a baseline can also be used to determine age-class effects and quantify their contribution to current and future stock changes. Table 23 shows how the age-class effect could be separated. Table rows 1) and 4) describe stock changes in forest biomass that actually occur. These deviate from C stock changes that would occur if the age-class structure would be different, e.g. a Normal Forest distribution or natural forest distribution.

A simple accounting scheme would just account for stock changes that occurred under the reference scenario. For the selected countries this would mean the following: all countries gain credits if the reference is Normal Forest. For countries like France and Poland that profited from their young forests, accountable amounts get smaller compared to 'gross-net'. Accounting longer rotations against the natural forest baseline leaves all countries with a debit, for Slovenia however, debits would be smaller compared to 'gross-net'. The situation for accounting of management change against one of the age-class baselines is less consistent. Choosing natural forest distribution would allow most countries to sign larger amounts than those that are actually occurring.

Table 23: Comparison of accountable biomass emissions and removals from forest management due to different initial conditions and management change in the second commitment period 2013-2017 in t C per ha and year.

	Scenario/ Accounting	Finland	France	Germany	Italy	Poland	Slovenia	Sweden	EU27
1)	LONGER' 'gross-net'	0.14	-0.26	-0.28	-0.16	-0.59	0.59	0.03	-0.15
2)	LONGER NF	-0.10	-0.16	-0.35	-0.01	-0.34	-0.34	-0.05	-0.17
3)	LONGER NatF	-0.53	-0.54	-1.02	-0.18	-0.99	-1.03	-0.29	-0.62
4)	SHORTER, 'gross-net'	0.22	-0.20	-0.13	-0.13	-0.41	0.61	0.07	-0.05
5)	SHORTER NF	0.05	-0.07	-0.14	0.04	-0.10	-0.20	0.03	-0.01
6)	SHORTER NatF	-0.30	-0.44	-0.79	-0.12	-0.73	-0.86	-0.17	-0.43

Factoring out of past practices as required by the Marrakesh Accords can be done computationally as presented here. However, depending on the baseline chosen, factoring out leads to accounting of stock changes that are not observed by the atmosphere. In addition, in some cases it might result in wrong incentives.

Another solution to the problem could be general regional discount factors. Similar to caps for the accountable C sink amount as implemented in the Kyoto Protocol, these regional factors would discount sinks and sources under Article 3.4 to direct human-induced effects. To account for regional differences in forestry history and disturbance regimes the factors could be established with the help of forest ecosystem models that account for disturbance and disturbance on a larger regional scale.

Individual exceptions and caps might help negotiators to find compromises. However, they also introduce loopholes and weaken the overall aim of the process. An efficient mitigation strategy requires more general rules for accounting.

SIX.4 Conclusions

As required by the Marrakesh Accords, past practice effects can be factored out if occurring stock changes are compared to a baseline. A reference is needed to exclude effects that are not related to recent forest management. However, reference scenarios have to be chosen carefully to ensure the right incentives.

The quantification of forest management mitigation potential in European countries helped in demonstrating effects of different accounting approaches. It identified 'winners' and 'losers' of each accounting option considered.

There is no accounting method that is most beneficial for all countries because initial conditions in countries vary. Accounting against a dynamic baseline (e.g. Business as Usual) results in accountable amounts that deviate from atmospheric signal above the forest. How much of the expected sink in some European countries can be accounted for under a future climate policy framework will thus be matter of negotiations.

With the help of forestry models like FORMICA the dynamic baseline approach can be used to establish an accounting scheme that is climate effective and creates incentives for climate change mitigation measures (such as rotation lengthening).

OVERALL CONCLUSIONS

This thesis investigated the potential of forest management to contribute to climate change mitigation. There are many biotic and abiotic factors which influence forest ecosystem (forest growth, biomass turnover, and decomposition), forestry sector (product use, efficiencies) and mitigation services through substitution. Some get effective on the stand level and others at regional level (past practices).

The forestry model FORMICA takes many of these factors into account and integrates over sectors, space and time. It is capable of assessing impacts of different forest management options on C stocks and fluxes in forest ecosystems, on C stored in harvested wood products and forest product derived fossil fuel C substitution as well as site-specific economic costs and revenues.

An important question is which land-use options are most effective for climate change mitigation and at the same time economically beneficial. A landscape with its diverse habitats allows several complementary strategies. FORMICA was used to show how forest and cropland management offer significant potential for cost efficient climate change mitigation.

The perspective on climate benefits matters. An ecosystem- and sector-centered view favors the conservation of forests and afforestation while a holistic system's perspective creates additional opportunities in classical timber production. Recycling of wood products for energy is more efficient than the production of dedicated energy wood. There is hence no climate change mitigation benefit from switching from timber to energy forestry.

Timber oriented forestry and forest conservation already deliver manifold carbon services without being financially rewarded, while agriculture leaves significant potential for bioenergy unexploited. Recycling of primary land-use products boosts the climate effectiveness of land-use measures and allows accommodating the competing pressures on the productive land resource.

To assess the mitigation potential more realistically model estimates have to incorporate uncertainty of underlying processes that are sensitive to model output.

Mitigation measures that consider a change in forest management have to have effects that exceed this uncertainty to be climate effective. FORMICA was used to highlight sensitive parameters which control different processes in different parts of the forestry sector C balance, e.g. maximum biomass controlling forest growth and the energy substitution factor controlling the yield of fossil fuel displacement.

It was shown that some parameters influence C pools in opposing directions. Rotation length decreases biomass C when it is shortened but increases carbon stored in products. This leads to the special feature that overall uncertainty might decrease with the level of aggregation.

The magnitude of the carbon sink potential thus varies along with the types of constraints considered and is highly sensitive to the region, time frame, management history and assumptions on future management. Considering an implementation level of 20% about 20 Mt C could be stored in ecosystem, harvested products and substituted in Thuringia between 2010 and 2050. It is crucial to incorporate uncertainty in model estimations of future forest sink development and management change projections to assess measure for climate change mitigation in forestry in a right way. Model sensitivity analysis helped to identify important parameters that need to be constrained sufficiently to reduce uncertainty of model output.

Carbon sinks and sources of managed forests on a regional scale are driven by the effects of past practices and natural disturbances, which can be explained on a theoretical basis. The statistics of disturbance regimes that dominate a forest landscape form the age-class structure that influences the current and future regional C balance.

According to the model, European countries will store around 20 Mt C, fixed in forest biomass, soil, litter and harvested wood products annually over the next decade. This uptake is only due to ecosystem aging, because other effects were not considered. The age-class induced sink in Europe is very likely to get smaller throughout the next 30 years by a rate of about 1 Mt C per year.

It was examined how different accounting schemes treat the observed stock changes and how age-class effects can be differentiated computationally from today's observable carbon dynamics in managed forest ecosystems. Depending on the accounting scheme and the reference chosen there can be 'winners' and 'losers' among countries with different age-class legacy. How much of the expected sink in some European countries can be accounted for under a future climate policy framework will thus be matter of negotiations.

In reality, disturbances and harvest are not constant over time and multiple disturbance types and harvest have formed forest age-class structures that are observed today. Practically, this makes the installation of a reasonable and credible reference baseline and thus a complete factoring out of past practices intractable. Nevertheless, the accounting against a dynamic prospective baseline can be a tool to create incentives for countries to change forest management practice towards options with larger mitigation potential.

The magnitude of forest management mitigation potential varies along with the types of constraints considered and is highly sensitive to the region, time frame and assumptions included in the calculations. Well balanced mitigation strategies need to take into account very different properties of mitigation measures.

1) Sequestration and conservation: The biosphere sink is manageable but also threatened by human activities. It is important to maintain biospheric C stocks and this should be the focus of international struggles. An increase of C stocks at the ecosystem level holds potential for a medium-term strategy. Temporal dynamics of future sinks and sources depend on age-class distribution and thus past disturbances.
2) Substitution: Forests of the future are more than ever under the pressure of multiple expectations (timber, bioenergy, diversity supply). Forest management requires even more balance between these forest services. Effective recycling along the product chain and fossil fuel substitution can free land for long-term sustained C sequestration by conservation. It can also take off pressure from natural or extensively managed ecosystems with high C stocks and potentially high emissions if management would be intensified.

SUMMARY

Motivation, aim and scope

The Fourth Assessment Report issued by the Intergovernmental Panel on Climate Change (IPCC) on February 2, 2007 identified more clearly then any other Assessment Report that the observed increase in global average temperatures during the last half century is due to the increase in atmospheric greenhouse gases (GHGs). Depending on the development of technologies and economy, emissions of fossil fuel burning will increase further. To avoid global warming that goes beyond 2 degrees above preindustrial levels, which is considered to be a 'dangerous' climate change, besides emission reduction other mitigation strategies have to be developed.

The terrestrial biosphere already absorbs approximately one third of annual anthropogenic CO_2 emissions. Among others, forest management is a major contributing process. The Kyoto Protocol aims at a reduction of GHG emissions. Sequestration of carbon in forest ecosystems induced by forest management is considered one strategy of mitigation that can be opted for by parties under the Kyoto Protocol. But mitigation services of managed forests go beyond sequestration, including storage in wood products and substitution of fossil fuel carbon by wood products and bioenergy.

However, parties and the scientific community lack detailed knowledge about what potential forest management actually has to mitigate climate change, at national to global, and decadal to centennial scales, and about associated uncertainties and constraints. This thesis explored the impact of past and present management on the forest C stocks and fluxes and quantified the potential for climate change mitigation. The aim of this study was:

1) to investigate specific potentials of forest management as a mitigation tool, considering that forest management has different impacts on C stocks and fluxes in forest ecosystems as well as on carbon stored in harvested wood products and on fossil fuels substituted.

2) to explore mechanisms that effect mitigation potential on different scales (stand versus regional level, integration over forestry sector), dimensions (climate benefit vs. financial revenue) and its temporal development.
3) to identify important parameters and associated uncertainties.
4) to factor out drivers of carbon sinks and sources of managed forests on a regional scale.
5) to compare accounting schemes for forest management and their qualification to create incentives for climate change mitigation.

Forest management in this thesis was limited to climate relevant activities that likely change carbon stocks and included forest regeneration, thinning and harvest quantity and timing, forest protection and product allocation. It looked predominantly on conditions in Europe. The scope was limited to managed forests and did not consider afforestation, reforestation or deforestation.

Structure and methodology

The basic technical structure of the thesis splits into four issues:

a) Development of a forest management model (Chapter Two), comprising the review of existing approaches of forest management carbon modeling, description of important processes that have to be considered in the design of such a model and formulation of algorithms.
b) Application of the model to plot level (Chapter Three), comparing management options on a hectare basis neglecting area information and an evaluation of model uncertainty and sensitivities related to uncertain parameters (Chapter Four).
c) Theoretical analysis of landscape level processes leading to carbon sinks and sources contrasted with accounting rules to incorporate them in a climate policy framework. (Chapter Five)
d) Comparison of model scenarios with different assumptions on future management change and initial conditions to quantify potentials for mitigation and factor out drivers on landscape level (Chapter Four, Five and Six).

The model FORMICA (FORest Management Impact on Carbon dynamics) is a dynamic inventory-based carbon tracking model. It aims to calculate carbon pool trajectories under current and changing forest management in existing forests at a regional scale. Forest growth is prescribed through biomass-increment functions that can be derived from yield tables or plot data. Biomass harvest can be parameterized to various forest management activities like planting, thinning and final harvest. Soil and litter pools are included as well as wood products and possible substitution effects of wood by other materials.

Data sources used by FORMICA varied with the purpose of application. How forest and cropland management offer significant potential for cost efficient climate change mitigation in particular was demonstrated in Chapter Three. The model application on plot level focused on Thuringian conditions and included also agricultural land-use options. Growth data were derived from regional yield tables (forests) and regional surveys (agriculture). Basic parameters of biomass properties and species-specific allocation to roots, branches and foliage were taken from literature. Aggregated data from the Thuringian forest inventory served as input data to initialize standing volume and age-class distribution. To assess implication of forest management for carbon stored in harvested wood products and efficiencies of fossil fuel substitution (product substitution and bioenergy) data from regional life cycle analyses were used. Regional prices and cost structures formed the basis for estimating net present values of possible land-uses.

The same dataset for Thuringia was used for a model sensitivity and uncertainty analysis, where FORMICA served as a tool to identify important parameters and estimate model uncertainty associated with parameters and input data.

Another application of FORMICA at larger scale aimed at processes on landscape level. Based on forest inventory data of European countries (among them Finland, France, Germany, Italy, Poland, Slovenia and Sweden), the purpose was here to factor out effects of past practices that formed today's age-class structure of forests which influences their potential for mitigation in the future. Allocation and other parameters were kept general and were taken from the literature. Different scenarios of future management and initial conditions were simulated and compared to quantify these effects.

Results and discussion

There is a significant potential for climate change mitigation through forest management by sequestration, conservation and fossil fuel substitution in managed forests. This thesis analyzed its impact on forest carbon stocks in various pools and on various scales.

The forest carbon sink in managed forest ecosystems is limited due to the nutrient-limited carrying capacity of forest stands and periodically occurring disturbances through harvest. Forest conservation can increase C stocks on that level. In managed forests fossil fuel substitution and use of long-lasting wood products can enhance the sink potential beyond the ecosystem.

Including additional mitigation services matters with respect to climate benefits and land-owner revenue. An ecosystem- and sector-centered view favors the conservation of carbon stored in forests while a holistic systems perspective highlights additional opportunities in long-rotation timber production and in particular for bioenergy production. Economic conditions in Thuringia have already created an almost optimum climate benefit from forestry where energy recycling of wood products is intense.

To assess the mitigation potential more realistically model estimates have to incorporate uncertainty of underlying processes that are sensitive to model output. FORMICA was used to highlight sensitive parameters which control different processes in different parts of the forestry sector C balance, e.g. maximum biomass controlling forest growth and the energy substitution factor controlling the yield of fossil fuel displacement.

It was shown that some parameters influence C pools in opposing directions. Rotation length decreases biomass C when it is shortened but increases carbon stored in products. This leads to the special feature that overall uncertainty might decrease with the level of aggregation.

However, also implications on stand and landscape level have to be considered in an assessment of forest management mitigation potential. Carbon sinks and sources of managed forests on a regional scale are driven by the effects of past practices and natural disturbances, which can be explained on a theoretical basis. The statistics of disturbance regimes that dominate a forest landscape form the age-class structure that influences the current and future regional C balance.

The magnitude of the carbon sink potential thus varies along with the types of constraints considered and is highly sensitive to the region, time frame, management history and assumptions on future management. On average 20 Mt C could be stored in ecosystem, harvested products and substituted in Thuringia between 2010 and 2050. The potential is similar for various management options (e.g. conservation, species change or rotation lengthening, considering an implementation level of 20%) if the total forestry sector mitigation service is considered. Differences between management options emerge on lower levels of aggregation, e.g. when looking at biomass.

Finally, the thesis looked at effects of past practices on regional carbon stocks. It was also examined how they can be differentiated computationally from carbon due to recent forest management. Presented approaches of an accounting of these effects were evaluated in terms of applicability, verifiability, and ability of providing incentives for good practice. Not all accounting schemes qualify to create incentives for climate change mitigation under a future climate policy framework. Factoring out of past practices is technically feasible but is depending on baseline definition.

According to the model, European countries will store around 20 Mt C, fixed in forest biomass, soil, litter and harvested wood products annually over the next decade. This uptake is only due to ecosystem aging, because other effects were not considered. The age-class induced sink in Europe is very likely to get smaller throughout the next 30 years by a rate of 1 Mt C per year. How much of this sink can be accounted for under a future climate policy framework will be matter of negotiations.

ZUSAMMENFASSUNG

Motivation und Aufgabenstellung

Der Vierte Sachstandsbericht des Zwischenstaatlichen Ausschusses für Klimawandel (IPCC) der am 2 Februar 2007 vorgestellt wurde, machte mehr als je ein anderer Bericht zuvor deutlich, dass der beobachtete Anstieg der globalen mittleren Temperatur während der letzten Hälfte des letzten Jahrhunderts auf einen Anstieg von Treibhausgasen (THG) in der Atmosphäre zurückzuführen ist.

Abhängig von der Entwicklung von Technologie und Wirtschaft wird die Konzentration von THGs durch die Verbrennung fossiler Energieträger weiter ansteigen. Um eine globale Erwärmung von über 2 Grad C über dem vorindustriellen Level, welche als ‘gefährlicher’ Klimawandel eingestuft wurde, zu verhindern, müssen Maßnahmen zur Emissionsreduzierung von zusätzlichen Minderungsstrategien flankiert werden.

Die terrestrische Biosphäre absorbiert bereits etwa ein Drittel der emittierten CO_2-Menge. Neben anderen Prozessen spielt Waldbewirtschaftung hierbei eine wichtige Rolle. Das Kioto-Protokoll hat eine Reduktion von THG-Emissionen zum Ziel. Speicherung von CO_2 in Form von Kohlenstoff (C) in Waldökosystemen und hervorgerufen durch Bewirtschaftungsmaßnahmen ist als Minderungsstrategie unter dem Protokoll anrechenbar und kann von Staaten gewählt werden. Aber die CO_2-Minderungsleistung durch Waldbewirtschaftung geht über die Speicherung auf Ökosystemebene hinaus, wenn Festlegung in geernteten Holzprodukten und die Substitution von CO_2 aus der Verbrennung fossiler Brennstoffe durch energiesparende Holzprodukte und Bioenergie berücksichtigt werden.

Allerdings haben teilnehmende Länder unter dem Protokoll und auch die Wissenschaft noch keine genauen Erkenntnisse darüber, welches Minderungspotenzial Waldbewirtschaftung konkret birgt. Auch darüber, wie sich dieses mit der Integration über räumliche, sektorale und zeitliche Skalen ändert, sowie Unsicherheiten und Beschränkungen ist wenig bekannt. Diese Doktorarbeit untersuchte die Auswirkungen, die

Waldbewirtschaftung unter der Berücksichtigung von Maßnamen in der Gegenwart aber auch Maßnahmen in der Vergangenheit, die maßgeblich Einfluss nehmen, hat. Sie hatte zum Ziel,

1) spezifische Potenziale der Waldbewirtschaftung als CO_2-Minderungsmaßnamen zu untersuchen, unter der Berücksichtigung, dass die Bewirtschaftung von Wäldern unterschiedliche Effekte auf Kohlenstoffspeicher und -flüsse in Waldökosystemen, aber auch auf den Kohlenstoffspeicher Holzprodukte hat.
2) Mechanismen zu identifizieren, die auf den verschieden Ebenen eine Rolle spielen: Auswirkungen auf regionaler und Bestandesebene, Klimawirkung und Kosten, Integration über den Forstsektor (Biomasse, Ökosystem, Forstsektor, Substitution) und zeitliche Entwicklung.
3) wichtige Parameter und die damit verbundenen Unsicherheiten auszumachen.
4) Einflussgrößen auf Kohlenstoffsenken und –quellen auf der regionalen Ebene bewirtschafteter Wälder herauszufiltern.
5) Anrechnungsmethoden für Waldbewirtschaftung und deren Eignung zur Schaffung von Anreizen zu Minderungsmaßnahmen zu vergleichen.

Der Begriff Waldbewirtschaftung wurde in dieser Doktorarbeit eingeschränkt auf Bewirtschaftungsmaßnahmen, die potenziell Kohlenstoffvorräte verändern können und beinhaltet ebenso Waldverjüngung, Durchforstungs- und Ernteintensitäten, Waldschutz und Holzverwendung. Sie betrachtete vornehmlich Bedingungen in Europa. Die Ausrichtung war auf bewirtschaftete Wälder beschränkt und berücksichtigte weder Aufforstungen, Wiederbewaldung noch Entwaldung.

Struktur und Vorgehensweise

Technisch lässt sich die Arbeit in vier Abschnitte einteilen:

a) Entwicklung eines Waldbewirtschaftungsmodels, um die wissenschaftlichen Fragestellungen zu beantworten (Kapitel Zwei). Dafür wurde Literatur zu bestehenden Modellierungsansätzen und wichtigen beteiligten Prozessen analysiert und Algorithmen formuliert, die diese beschreiben.
b) Anwendung des Models auf Plotebene (Kapitel Drei), welche verschiedene Optionen der Bewirtschaftung auf Hektarebene vergleicht und Untersuchung und Bewertung von Unsicherheiten und Sensitivität von Modellparametern beinhaltet (Kapitel Vier).

c) Theoretische Analyse der treibenden Prozesse auf Landschaftsebene, die Quellen und Senken verursachen und eine Gegenüberstellung mit Anrechnungsregeln, wie diese in einem politischen Klimaschutzrahmen berücksichtigt werden könnten (Kapitel Fünf).
d) Vergleich von Modellszenarien mit verschiedenen Annahmen über die zukünftige Entwicklung der Waldbewirtschaftung, um Minderungspotenzial zu quantifizieren und Einflussgrößen auf Landschaftsebene konkret herauszufiltern (Kapitel Vier, Fünf und Sechs).

Das FORMICA-Modell (FORest Management Impact on Carbon dynamics) ist ein dynamisches Forstbewirtschaftungsmodell, das auf Inventaren basiert und Kohlenstoffvorräte und -vorratsänderungen verfolgt. Es kann angewendet werden, um die Kohlenstoffdynamik heutiger und zukünftiger Waldbewirtschaftung auf regionaler Ebene zu berechnen. Waldwachstum wird darin in Form von Biomasse-Zuwachsfunktionen modelliert, welche aus forstlichen Ertragstafeln oder Probeflächen gewonnen werden können. Ernte von Biomasse kann in Form verschiedener Maßnamen parametrisiert werden, wie z.B. Bestandesbegründung, Durchforstungen und Endnutzung. Boden- und Streupools werden in angegliederten Modellen berücksichtigt, wie auch Holzprodukte und deren potenzielle Substitution fossiler Brennstoffe.

Datenquellen für das Modell können verschieden sein, je nach Ausrichtung der Anwendung, der es dienen soll. In welcher Weise Forstwirtschaft und Landwirtschaft Potenziale kosteneffizienter und klimaeffektiver CO_2-Minderung realisieren können wurde mit Hilfe des Modells untersucht (Kapitel Drei). Die Anwendung auf Bestandesebene basierte auf Daten aus Thüringen. Wachstumsdaten dafür wurden aus Ertragstafeln (Forstwirtschaft) und regionalen Erhebungen (Landwirtschaft) abgeleitet. Grundlegende Parameter, die Biomasse und deren Umsetzung beschreiben wie auch art-spezifische Allokationsparameter für die Modellierung von Kohlenstoff in Ast-, Blatt- und Wurzelbiomasse wurden der Literatur entnommen. Aggregierte Daten aus Thüringer Forstinventaren dienten als Eingangsgrößen für die Initialisierung von Bestandesvolumen und Altersklassenverteilung. Zur Abschätzung der Auswirkungen von Waldbewirtschaftung auf Kohlenstoff in Holzprodukten und die Wirksamkeit von Produkt- und Energiesubstitution wurden Daten aus regionalen Lebensweganalysen verwendet. Regionale Preis- und Kostenstrukturen bildeten die Grundlage für die Berechnung des Kapitalwerts einzelner Optionen für eine ökonomische Bewertung.

Der gleiche Datensatz diente einer Analyse der Sensitivität wichtiger Modellparameter und ihrer Unsicherheit. FORMICA wurde hier eingesetzt, um wichtige Modellparameter zu identifizieren und Modellunsicherheiten durch Parameterunsicherheit zu bestimmen.

Eine weitere Anwendung des Modells zielte auf Prozesse auf Landschaftsebene ab. Grundlage waren für diese Studien Forstinventardaten aus verschiedenen europäischen Ländern (u.a. Finnland, Frankreich, Deutschland, Italien, Polen, Slowenien und Schweden). Der Zweck dieser Analyse war die Separierung von Effekten durch Altersklassenstruktur auf heutige und zukünftige Minderungspotenziale. Parameter wurden auch hier größtenteils der Literatur entnommen. Hinzu kam die Berücksichtigung verschiedener Management- und Altersklassenszenarien, die miteinander verglichen wurden, um derartige Effekte sichtbar zu machen.

Ergebnisse und Diskussion

Es gibt ein maßgebliches Potenzial zur CO_2-Minderung durch Waldbewirtschaftung in der Form von C Einlagerung in Waldökosystemen und dem Forstsektor, den Schutz der C-Vorräte und die Substitution fossiler Brennstoffe. Die vorliegende Arbeit untersuchte deren Mechanismen auf verschiedenen Ebenen, Zeitskalen und Dimensionen.

Die Kohlenstoffsenke in bewirtschafteten Wäldern ist begrenzt durch natürliche Tragfähigkeit und periodische Störungen durch (menschliche) Eingriffe. Die Einstellung von Erntemaßnamen kann allerdings Vorräte im Wald erhöhen. Bewirtschaftung birgt aber auch das Potenzial der Speicherung von C in langlebigen Holzprodukten oder durch die Substitution fossiler Brennstoffe durch Holzprodukte und Bioenergie. Eine Berücksichtigung von Minderungsleistungen der Waldbewirtschaftung über Ökosystemgrenzen hinaus ist wichtig in Hinsicht auf die Ausschöpfung des Minderungspotenzials, aber auch auf finanzielle und ökonomische Aspekte. Die wirtschaftliche Situation in Thüringen führte bereits zu einem hohen Grad an Klimaeffektivität der Waldbewirtschaftung.

Für eine realistische Bewertung des Minderungspotenzials müssen Modelluntersuchungen die Unsicherheiten von Modellparametern und Eingangsvariablen berücksichtigen. In einer Sensitivitätsanalyse mit FORMICA wurden wichtige Parameter bestimmt, die auf verschiedenen Ebenen wirken, z.B. maximale Biomasse, welche Waldwachstum beeinflusst oder Substitutionseffizienz, welche den Grad der Ersetzung fossiler Brennstoffe bestimmt. Darunter gibt es Parameter, die auf unterschiedliche Pools entgegengesetzte Wirkungen haben. So verringert eine Verkürzung der Umtriebszeit die Menge an Kohlenstoff, die in Biomasse gespeichert ist, gleichzeitig erhöht dies aber die Vorräte in Holzprodukten. Diese besondere Eigenschaft führt dazu, dass die Gesamtunsicherheit mit dem Aggregierungsgrad sinken kann.

Neben den Auswirkungen verschiedener Formen der Waldbewirtschaftung auf Hektarebene gibt es Effekte auf Landschaftsebene, die das zukünftige Minderungspotenzial von Wäldern nachhaltig beeinflussen. Kohlenstoffsenken und –quellen in bewirtschafteten Wäldern hängen auf Landschaftsebene eng von Altersklasseneffekten ab, die durch Bewirtschaftung und Störungen in der Vergangenheit bedingt sind.

Das Potenzial, durch Waldbewirtschaftung CO_2-Konzentrationen zu verringern, unterscheidet sich je nach regionalen Bedingungen, dem Zeithorizont und der zukünftigen Entwicklung der Bewirtschaftungsweise. Für Thüringen ermittelte das Modell im Mittel ein biologisch-technisches Potenzial von 20 Mt C, welches durch Speicherung in Biomasse, Boden und Streu, Holzprodukten und durch Energie- und Produktsubstitution zwischen 2010 und 2050 realisiert werden könnte. Dabei unterscheiden sich verschiedene Managementmaßnamen (z.B. Einstellung der Bewirtschaftung, Baumartenwechsel zu mehr Laubholz oder Verlängerung der Umtriebszeit, bei einer Umsetzung auf 20% der Waldfläche) weniger stark, wenn alle Pools und Leistungen summiert werden.

Die Arbeit untersuchte speziell die Auswirkungen durch Störungen und Bewirtschaftung in der Vergangenheit, die Minderungspotenziale durch Altersklasseneffekte auf Landschaftsebene beeinflussen. Eine wichtige Rolle dabei spielt, ob diese von rein rezenten Bewirtschaftungseffekten getrennt werden können. Verschiedene Methoden der Anrechnung solcher Effekte wurden in Bezug auf ihre Anwendbarkeit und Verifizierbarkeit verglichen. Nicht alle Anrechnungsmethoden schufen Anreize für klimafreundliche Waldbewirtschaftung. Die konkrete Trennung von Altersklasseneffekten hängt dabei von der Wahl der Referenzlinie ab, die allerdings schwer zu ziehen ist.

Angewandt auf europäische Länder ermittelte FORMICA eine Senke des Gesamtsektors (Wald und Holzprodukte) für das kommende Jahrzehnt von jährlich etwa 20 Mt C. Diese Aufnahme wird allein durch die Alterung europäischer Wälder hervorgerufen. Die alterungsbedingte Senke in Europa wird über die nächsten 30 Jahre um etwa 1 Mt C pro Jahr abnehmen, sollte die momentane Bewirtschaftung beibehalten werden. Wie viel von dieser Senke letztendlich von Ländern unter dem Kioto-Protokoll und eventuellen Nachfolgeverträgen angerechtet werden kann, wird Verhandlungssache sein.

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APPENDIX

Table A1: Table of parameter values for Thuringian forestry options. Data sources: (1) global value; (1) Wirth et al., 2003; (2) Burschel et al., 1993; (3) Satoo, 1971 according to White et al., 2000; (4) Mälkönen, 1974 according to White et al., 2000; (4) Mund, 2004 ; (5) Wirth et al., 2004; (6) Lehtonen et al., 2004; (6) for roots we assumed the same uncertainty as for branches due to lack of data ; (7) Enquist and Niklas, 2002; (8) Assmann, 1963; (9) Dittmar et al., 1983; (10) Lembcke et al., 1975; (11) Erteld, 1961; (12) Assmann, 1961 (13) Masera et al., 2003; (14) spruce, Assmann, 1961; others estimated from yield tables; (15) Kouba, 2002; (16) Freibauer et al., submitted; (x)data without reference from expert guess.

Parameter group	Parameter	Unit	Spruce	Beech	Pine	Oak	Source
Carbon concentration	foliage	[%]	0.5	0.5	0.5	0.5	(1 all spec.)
	stem	[%]	0.5	0.5	0.5	0.5	(1 all spec.)
Wood density		[%]	0.37	0.56	0.43	0.56	(2,1,1,1)
Turnover rate	branches	[1/yr]	0.04	0.03	0.02	0.02	(5,4,5,x)
	foliage	[1/yr]	0.20	1.00	0.40	1.00	(3,x,4,x)
	roots	[1/yr]	0.04	0.03	0.02	0.02	(6 all spec.)
Non-woody litter	soluble	[%]	0.27	0.38	0.27	0.38	(13 all spec.)
	holocellulose	[%]	0.51	0.36	0.51	0.36	(13 all spec.)
	lignin-like	[%]	0.22	0.26	0.22	0.26	(13 all spec.)
Fine-woody litter	soluble	[%]	0.03	0.03	0.03	0.03	(13 all spec.)
	holocellulose	[%]	0.65	0.65	0.65	0.65	(13 all spec.)
	lignin-like	[%]	0.32	0.32	0.32	0.32	(13 all spec.)
Coarse-woody litter	soluble	[%]	0.03	0.03	0.03	0.03	(13 all spec.)
	holocellulose	[%]	0.69	0.75	0.69	0.75	(13 all spec.)
	lignin-like	[%]	0.28	0.22	0.28	0.22	(13 all spec.)
Allocation branches	β 0	coeff	0.245	2.590	-2.301	2.590	(5,6,7,6)
	β 1	coeff	1.097	1.000	0.950	1.000	(5,6,7,6)
	β 2	coeff	0.019	0.000	0.000	0.000	(5,6,7,6)
Allocation foliage	β 0	coeff	0.106	0.120	-2.253	0.120	(5,6,7,6)
	β 1	coeff	0.591	0.750	0.780	0.750	(5,6,7,6)
	β 2	coeff	0.011	0.000	0.000	0.000	(5,6,7,6)
Allocation roots	β 0	coeff	0.325	2.590	-3.320	2.590	(5,6,7,6)
	β 1	coeff	0.000	1.000	1.140	1.000	(5,6,7,6)
	β 2	coeff	0.000	0.000	0.000	0.000	(5,6,7,6)
Management mort.	fraction of biomass	[%]	0.10	0.05	0.05	0.05	(x all spec.)
	impact time	[yrs]	10.00	5.00	5.00	5.00	(x all spec.)

Table A1 continued.

Parameter group	Parameter	Unit	Spruce	Beech	Pine	Oak	Source
Growth class 1	α 0	coeff	0.1	0.1	0.1	0.1	(8,9,10,11)
	α 1	coeff	-0.0198	-0.0075	-0.0306	-0.0205	(8,9,10,11)
	α 2	coeff	11.19	6.33	10.12	5.88	(8,9,10,11)
Max volume, growth class 1		[m3/ha]	1000	750	600	700	(14 all spec.)
Growth class 2	α 0	coeff	0.1	0.1	0.1	0.1	(8,9,10,11)
	α 1	coeff	-0.0163	-0.0076	-0.0301	-0.0198	(8,9,10,11)
	α 2	coeff	8.76	5.96	8.69	5.29	(8,9,10,11)
Max volume, growth class 2		[m3/ha]	800	700	500	670	(14 all spec.)
Growth class 3	α 0	coeff	0.1	0.1	0.1	0.1	(8,9,10,11)
	α 1	coeff					(8,9,10,11)
	α 2	coeff					(8,9,10,11)
Max volume, growth class 3		[m3/ha]	700	650	550	640	(14 all spec.)
Risk wind	c	coeff	0.20	-	-	-	(15 all spec.)
	α	coeff	4.20	-	-	-	(15 all spec.)
	λ	coeff	3.50E-10	-	-	-	(15 all spec.)
Substitution factor Thuringia		coeff	0.57	0.57	0.57	0.57	(16 all spec.)

Table A2: Table of parameter values for Thuringian agriculture options. Data sources: (1) global value; (2) ; (3) global average of several authors; (4) Masera et al., 2003; (5) Filya, 2003; (6) values for beech from Table A1; (7) Vetter, A. personal communication and TMLNU, 2005; (8) Freibauer et al., submitted.

Parameter group	Parameter	Unit	Poplar	Wheat	Reference
Carbon content	foliage	[%]	0.50	0.47	(1,2)
	stem	[%]	0.50	0.47	(1,2)
Wood density		[%]	0.40	-	(3)
Turnover rate	branches	[1/yr]	0.04	1.00	(x,1)
	foliage	[1/yr]	1.00	1.00	(x,1)
	roots	[1/yr]	0.02	1.00	(x,1)
Non-woody litter	soluble	[%]	0.38	-	(4)
	holocellulose	[%]	0.36	-	(4)
	lignin-like	[%]	0.26	-	(4)
Fine-woody litter	soluble	[%]	0.03	0.04	(4,5)
	holocellulose	[%]	0.65	0.76	(4,5)
	lignin-like	[%]	0.32	0.20	(4,5)
Coarse-woody litter	soluble	[%]	0.03	-	(4)
	holocellulose	[%]	0.75	-	(4)
	lignin-like	[%]	0.22	-	(4)
Allocation branches	β 0	coeff	2.590	-	(6)
	β 1	coeff	0.120	-	(6)
	β 2	coeff	0.019	-	(6)
Allocation foliage	β 0	coeff	0.120	-	(6)
	β 1	coeff	0.591	-	(6)
	β 2	coeff	0.011	-	(6)
Allocation roots	β 0	coeff	2.590	-	(6)
	β 1	coeff	0.000	-	(6)
	β 2	coeff	0.000	-	(6)
Growth class 1		[m3/ha/a]	38	20.0	(7)
Growth class 2		[m3/ha/a]	30.6	13	(7)
Growth class 3		[m3/ha/a]	17	13	(7)
Substitution factor Thuringia		coeff	0.57	0.49	(8)

Table A3: Parameters to describe forest management options for Thuringia for four different species. Timber describes classical rotation forestry for producing timber, CC refers to continuous cover forestry. Data sources: (1) Assmann, 1963; (2) Dittmar et al., 1983; (3) Lembcke et al., 1975; (4) Erteld, 1961; (5) Pistorius and Profft, personal communication; (6) Wutzler, personal communication; (7) Pistorius and Profft, personal communication; (8) Mund et al., 2006; (9) Wirth et al 2003; (10) Freibauer et al submitted; (x) data without reference from expert guess.

Parameter	Spruce		Beech		Pine	Oak	References
	timber	CC	timber	CC	timber	timber	
Thinning1 first year	30	30	40	30	30	40	(1,2,3,4)
Thinning1 interval	10	10	15	15	10	15	(1,2,3,4)
Thinned fraction of total biomass	0.20	0.20	0.15	0.15	0.20	0.15	(1,2,3,4)
Fraction of stem to slash	0.20	0.20	0.20	0.20	0.20	0.40	(x all spec.)
Fraction of branch to slash	1.00	1.00	1.00	1.00	1.00	1.00	(x all spec.)
Fraction of foliage to slash	1.00	1.00	1.00	1.00	1.00	1.00	(x all spec.)
Fraction of stem to sawn wood	0.00	0.00	0.00	0.00	0.00	0.00	(5 all spec.)
Fraction of stem to pulp wood	0.80	0.80	0.50	0.50	0.80	0.80	(5 all spec.)
Fraction of stem to energy wood	0.20	0.20	0.50	0.20	0.20	0.20	(5 all spec.)
Thinning2 first year	70	50	120	80	50	100	(1,2,3,4)
Thinning2 interval	10	10	15	10	15	15	(1,2,3,4)
Thinned fraction of biomass	0.15	0.30	0.40	0.20	0.20	0.10	(1,2,3,4)
Fraction of stem to slash	0.10	0.10	0.25	0.25	0.10	0.3	(x all spec.)
Fraction of branch to slash	1.00	1.00	1.00	1.00	1.00	1.00	(x all spec.)
Fraction of foliage to slash	1.00	1.00	1.00	1.00	1.00	1.00	(x all spec.)
Fraction of stem to sawn wood	0.30	0.30	0.10	0.55	0.30	0.10	(5 all spec.)
Fraction of stem to pulp wood	0.50	0.50	0.30	0.15	0.50	0.30	(5 all spec.)
Fraction of stem to energy wood	0.20	0.20	0.60	0.30	0.20	0.60	(5 all spec.)
Harvest age	100	9999	150	9999	110	200	(6 all spec.)
Harvested fraction of biomass	0.95	0	0.75	0	0.95	0.95	(7,8 all spec.)
Fraction of stem to slash	0.1	0.1	0.1	0.1	0.1	0.1	(7,8 all spec.)
Fraction of branch to slash	1.00	1.00	0.50	0.50	0.7	0.7	(7,8 all spec.)
Fraction of foliage to slash	1.00	1.00	1.00	0.00	1.00	1.00	(7,8 all spec.)
Fraction of stem to sawn-wood	0.80	0.80	0.55	0.55	0.80	0.55	(7,8 all spec.)
Fraction of stem to pulp wood	0.16	0.16	0.40	0.40	0.16	0.40	(7,8 all spec.)
Fraction of stem to energy wood	0.04	0.04	0.00	0.00	0.04	0.00	(7,8 all spec.)
MRT of sawn-wood	30	30	40	40	30	40	(9 all spec.)
MRT of pulp wood	2	2	2	2	2	2	(9 all spec.)
MRT of energy wood	2	2	2	2	2	2	(9 all spec.)
Fraction sawn wood to energy	0.6	0.6	0.6	0.6	0.6	0.6	(10 all spec.)
Fraction pulp wood to energy	0.6	0.6	0.6	0.6	0.6	0.6	(10 all spec.)
Product subst. factor sawn-wood	0.24	0.24	0.16	0.16	0.16	0.16	(10 all spec.)

Table A4: Parameters used in YASSO model. Data sources: Wirth et al., 2003.

Parameter	Unit	Spruce	Beech	Pine	Oak
Annual average temperature	[°C]	9.3	9.3	9.3	9.3
Precipitation in growing season	[mm]	344	344	344	344
Evapotranspiration in growing season	[mm]	590	590	590	590

Table A5: Initial values for stem volume Thuringia. Data source: Wirth et al., 2003.

Age class midpoint	Unit	Spruce	Beech	Pine	Oak
10	[m^3 ha^{-1}]	10	20	23	61
30	[m^3 ha^{-1}]	140	40	209	107
50	[m^3 ha^{-1}]	270	220	326	250
70	[m^3 ha^{-1}]	370	340	395	375
90	[m^3 ha^{-1}]	400	400	386	429
110	[m^3 ha^{-1}]	400	410	372	429
130	[m^3 ha^{-1}]	390	390	358	418
150	[m^3 ha^{-1}]	380	360	349	393
170	[m^3 ha^{-1}]	350	340	358	382
> 180	[m^3 ha^{-1}]	410	320	349	357

Table A6: Revenues and costs for different management options in Euros. Costs differ with slope classes. The values represent costs for slope class “flat” (<15%). Costs for skidding are supposed to rise by 25% in slope class “medium” and 100% at “steep” slopes compared to costs listed here. These differences are due to special equipment (like cable way) needed for timber extraction at steep slopes. Costs for thinning rise only in the the “steep” class by 15% on average due to the need for special machines. Harvest costs (motor manual with chain saw) are assumed to be constant over slope classes. All data from expert interviews, except subsidies: *) TMLNU, 2004 and BMELV, 2006; **) TMLNU, 2006.

	Unit	Spruce timber	Spruce energy	Beech timber	Beech conservation
Revenue land subsidies *	[1/ha/year]	0	0	0	0
Revenue bonus (here: for old growth above harvest age) **	[1/ha/year]	0	0	0	120
Revenue sawn-wood	[1/m3]	60	0	70	0
Revenue pulp wood	[1/m3]	20	0	25	0
Revenue energy wood	[1/m3]	30	30	30	0
Revenue food	[1/t DM]	0	0	0	0
Costs planting/establishment	[1/ha]	1450	1450	0	0
Costs fencing once	[1/ha]	0	0	1600	0
Costs thinning 1 (harvester)	[1/m3]	11.50	0	11.50	0
Costs thinning 2 (harvester)	[1/m3]	11.50	0	11.50	0
Costs harvest (motor manual)	[1/m3]	14.00	14.00	14.00	0
Costs skidding	[1/m3]	8.00	8.00	8.00	0

Table A7: Revenues and costs for different agricultural options in Euros. All data from expert interviews, except subsidies: *) TMLNU, 2004 and BMELV, 2006; **) TMLNU, 2006.

	Unit	Oak afforestation	Poplar energy	Wheat energy	Wheat food + straw energy	Wheat food
Revenue land subsidies *	[1/ha/year]	0	367.1	367.1	322.1	322.1
Revenue bonus (here: for afforestation) **	[1/ha/year]	300	0	0	0	0
Revenue sawn-wood	[1/m3]	60	0	0	0	0
Revenue pulp wood	[1/m3]	20	0	0	0	0
Revenue energy wood	[1/m3]	30	23	66	56	0
Revenue food	[1/t DM]	0	0	0	105	105
Costs planting/establishment	[1/ha]	2900	322	213	213	213
Costs fencing once	[1/ha]	1600	0	0	0	0
Costs thinning 1 (harvester)	[1/m3]	11.50	17	0	0	0
Costs thinning 2 (harvester)	[1/m3]	11.50	17	0	0	0
Costs harvest (motor manual)	[1/m3]	14.00	28	56	56	56
Costs skidding	[1/m3]	8.00	0	0	0	0