The impact of silvicultural strategies and climate change on carbon sequestration and other forest ecosystem functions

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Abstract

Forests are a key resource serving a multitude of functions such as providing income to forest owners, supplying industries with timber, protecting water resources, providing habitat for wildlife, and maintaining biodiversity. Recently much attention has been given to the role of forests in the global carbon cycle and their management for increased carbon sequestration is seen as a possible mitigation option against climate change. Furthermore, the use of harvested wood can contribute to the reduction of atmospheric carbon and other greenhouse gases through (i) carbon sequestration in wood products, (ii) the substitution of non-wood products with wood products, which in most cases are less energy intensive during their life cycle, and (iii) through the use of wood as a biofuel to replace fossil fuels. Forest resource managers are challenged by the task to balance these multiple and often conflicting forest functions while simultaneously meeting economic requirements and taking into consideration the demands of stakeholder groups. Additionally, risks and uncertainties with regard to uncontrollable external variables such as climate have to be considered in the decision making process.

In this study a scientific stakeholder dialogue with forest-related stakeholder groups in the Federal State of Brandenburg was accomplished offering a valuable opportunity to bring together the specific knowledge of scientists, forest service personnel, and environmentalists and thereby provide a link to real life in a scientific study. The main results of this dialogue were the definition of major forest functions (carbon sequestration, groundwater recharge, biodiversity, and timber production) and priority setting among them by the stakeholders using the pair-wise comparison technique.

Following the stakeholder dialogue, the impact of different forest management strategies and climate change scenarios on the main functions of forest ecosystems were evaluated at the stand level and forest management unit level. The study was based on the current forest conditions in the Kleinsee management unit in south-east Brandenburg, which is dominated by Scots Pine (*Pinus sylvestris* L.) and oak (*Quercus robur* L. and *Quercus petraea* Liebl.) stands. Forest management strategies were simulated over 100 years using the forest growth model 4C and a newly implemented wood product model (WPM). A current climate scenario and two climate change scenarios based on global circulation models (GCMs) HadCM2 and ECHAM4-OPYC3 and the IS92a emission scenario were applied. The climate change scenario positively influenced stand productivity, and hence increased carbon sequestration (up to 27%) and income. The impact on the other forest functions was small.

Furthermore, the overall utility of forest management strategies were compared under the priority settings of stakeholders by a multi-criteria analysis (MCA) method. Significant differences in priority setting and the choice of an adequate management strategy were found for the environmentalists on one side and the more economy-oriented forest managers of public and private owned forests on the other side. From an ecological perspective, a conservation strategy would be preferable under all climate scenarios, but the business as usual management would also fit the expectations under the current climate due to high biodiversity and carbon sequestration in the forest ecosystem. In contrast, a forest manager in public-owned forests or a private forest owner would prefer a management strategy with an intermediate thinning intensity and a high share of pine stands to enhance income from timber production while maintaining the other forest functions.

The analysis served as an example for the combined application of simulation tools and a MCA method for the evaluation of management strategies at the stand and management unit levels under multi-purpose and multi-user settings with changing climatic conditions.

Another focus of this study was set on quantifying the overall effect of forest management on carbon sequestration in the forest sector and the wood industry sector plus substitution effects over 50 years. To achieve this objective, the carbon emission reduction potential of material and energy substitution (S_{mat} and S_{en}) was estimated based on data extracted from the literature. On average, for each tonne of dry wood used in a wood product substituting a non-wood product, 0.71 fewer tonnes of fossil carbon are emitted into to the atmosphere. Based on S_{mat} and S_{en} the calculation of the carbon emission reduction through substitution was implemented in the WPM. Carbon sequestration and substitution effects of different management strategies were simulated at three local scales using the WPM and the forest growth models 4C (management unit level) or EFISCEN (federal state of Brandenburg and Germany). An investigation was conducted on the influence of uncertainties in the initialisation of the WPM, S_{mat}, and basic conditions of the wood product sector on carbon sequestration plus substitution effects. Results showed that carbon sequestration in the wood industry sector plus substitution effects exceeded sequestration in the forest sector. In contrast to the carbon pools in the forest sector, which acted as sink or source, the substitution effect continually reduced carbon emission as long as forests are managed and timber is harvested. The main climate protection function was investigated for energy substitution which accounted for about half of the total carbon sequestration plus substitution effects, followed by carbon storage in landfills. In Germany, the absolute annual carbon sequestration in the forest and wood industry sector plus substitution effects was 19.9 Mt C. Over 50 years the wood industry sector contributed 70% of the total carbon sequestration plus substitution effects.

Contents

List of Tables

List of Figures

Chapter 1

The impact of silvicultural strategies and climate change on carbon sequestration and other forest ecosystem functions

1.1 Introduction

1.1.1 Background

The beginning of human settlement initiated changes in natural forest ecosystems. The extent of forest ecosystems was reduced by clearings and the structure and species' composition of the remaining forests were changed through the centuries by increasing manifold uses of forest goods and services such as domestic wood use, food foraging, wood pasture, and tar burning. At the end of the 18th century, the forests in Germany were devastated due to the high demand of wood needed by the industry, intensive wood pasture and litter raking. During this time some foresters introduced systematic forest management for the recovery of the forest ecosystem and to ensure a sustainable timber supply. Until the 20th century, forest management in many places in Germany focused mainly on timber production using coniferous species, monoculture forestry and clear-cut systems often leading to non-site adapted, delicate, instable forest ecosystems. In the second half of the 20th century, forest management at national and international levels focused more and more on other forest functions aside from timber production, such as the conservation and sustainable use of biological diversity, social functions and sequestration of carbon in order to combat global warming (Häusler and Scherer-Lorenzen 2002) and management strategies to maintain, conserve, restore and/or appropriately enhance forest functions have been developed. Among other authors, Maser et al. (1979), Hilt and Ammer (1994), Kangas and Pukkala (1996), Ammer and Schubert (1999), Lindhe et al. (2004), Majunke et al. (2004) and Schuck et al. (2004) investigated ways to improve the biodiversity and stability of forest ecosystems by increasing the amount of dead wood and species diversity. Other forest functions, such as fresh water supply and soil protection have been investigated by Vacik and Lexer (2001).

Special focus is set on the climate protection function of forest ecosystems. Forest ecosystems represent a substantial part of the present-day terrestrial uptake of the climate-relevant carbon dioxide (CO_2) by sequestration of carbon in their biomass and soils (IPCC

2001, 2007; Puhe and Ulrich 2001; Schimel et al. 2001). CO_2 contributes about 50% of the total greenhouse gas emissions at present and its atmospheric concentration has risen steadily since the onset of industrialisation and, by far, exceeds the natural range over the last 650,000 years (IPCC 2007). Specifically, fossil fuel burning and land-use changes are the causes of the increase in atmospheric carbon dioxide concentrations from a pre-industrial value of 280 ppm[3] to 379 ppm[3] in 2005 (IPCC 2007). Estimates of carbon sequestration for Europe assume that about 7 to 12% of the European emission is sequestrated in terrestrial biosphere (Janssens et al. 2003), which is about 135 to 209 Tg C a^{-1}. Carbon gains are observed in forest ecosystems and grassland soils, while croplands and peat are carbon sources. The causes for the high uptake in European forests are a combination of growth stimulation due to CO_2-fertilisation (Schimel 1995), nitrogen fertilisation (Spiecker et al. 1996), increased productivity because of global warming (e.g. longer growing seasons) and European forests being in the exponential growth phase because of a shift in age-structure towards young forest stands (Karjalainen et al. 1999; UN-ECE/FAO 2000; Nabuurs et al. 2003). In Germany, carbon sequestration estimates in forest ecosystems range between 0.143 Mg C ha^{-1} a^{-1} and 0.645 Mg C ha^{-1} a^{-1} (Dieter and Elsasser 2002; Janssens et al. 2005). Additionally, forests managed for timber supply can affect the amount of CO_2 in the atmosphere by (i) carbon sequestration in wood products, (ii) substitution of fossil fuels with biofuel, and (iii) substitution of products of energy intensive materials with equivalent wood products (Burschel et al. 1993; Karjalainen 1996; Schlamadinger and Marland 1996; Wegener and Zimmer 2001; Eggers 2002; Briceño-Elizondo and Lexer 2004; Janssens et al. 2005; Petersen and Solberg 2005; Werner et al. 2005; Kohlmaier et al. 2007).

Not only do the diverse demands on forest ecosystems lead to changes in forest management practices, but also the predicted impact of climate change on forest ecosystems force forest managers to adopt forest management (Müller 1997; Lindner et al. 2000; Garcia-Gonzalo et al. 2005; Briceño-Elizondo et al. 2006). Climate change will lead to an increase in temperature, CO_2 concentration, and changes in precipitation rates and pattern leading to profound changes in European forest ecosystems (Jarvis 1998; Kellomäki et al. 2005; Schaphoff et al. 2006; Zaehle et al. 2007) by influencing forest growth and productivity of forest species and, therefore, the competitive relationships among the species, the potential species composition of unmanaged forests, and the choice of species in managed forests through the alteration of precipitation patterns and temperature. Increasing temperature and CO_2 concentration will lead to a northward migration of the boreal tree line and enhance forest productivity if precipitation is not a limiting factor (northern boreal zone) or if precipitation is also increasing (temperate maritime zone). Otherwise, if the precipitation rate is decreasing, forest ecosystems will most likely suffer losses in productivity (temperate continental zone, Mediterranean zone; Kellomäki and Leinonen 2005). Furthermore, extreme events such as storms, floods, and droughts are predicted to occur more frequently and with higher intensity leading to a higher vulnerability of forest ecosystems and high losses in productivity (Ciais et al. 2005; Kellomäki et al. 2005). Those changes in climate call for an adaptation of forest management strategies depending on the predicted changes in each region by choosing the appropriate tree species, increasing the portion of mixed forest types, and maintaining a high species and structural diversity for example (Kellomäki et al. 2005). Then, forest ecosystems will be further able to provide forest goods and services such as fresh water supply, biodiversity, climate protection, and timber.

1.1.2 Objectives of this study

The overall objective of this study is the investigation of the impact of forest management strategies on diverse forest functions under current climate and climate change scenarios and to quantify the priority of the forest management strategies through the perspective of different stakeholder groups and their objectives for forest management. Special emphasis is placed on the climate protection function of forest ecosystems by carbon sequestration in the forest sector, in the wood industry sector, and the reduction of carbon emissions through material substitution and energy substitution. This overall objective is specified as follows:

1. Assessment of important forest functions and their indicators in cooperation with local stakeholder groups. Quantification of the priority of forest functions to different stakeholder groups.

2. Adaptation and integration of the wood product model (WPM) developed by Eggers (2002) in 4C to study carbon fluxes in the wood product chain.

3. Investigation of the impact of different forest management strategies on forest functions at the stand and regional levels. Evaluation and quantification of the priority settings of stakeholders with respect to the choice of forest management strategies through application of an appropriate multi-criteria analysis technique.

4. Development, parameterisation and integration of a routine within in the WPM to investigate the effect of material and energy substitution on carbon emissions. Identification and evaluation of uncertainties in the parameterisation of material substitution and uncertainties due to changes in framing conditions in the wood industry sector.

5. Assessment of the carbon balance of forest management strategies at three spatial scales (forest management unit, federal state of Brandenburg and Germany) under the aspect of a combined analysis of the forest sector and the wood industry sector including substitution.

1.1.3 Structure of this study

This thesis is structured into a general section (Chapter1) and a publication section (Chapters 2 to 5). Section 1.2 includes a detailed description of the applied models (4C and WPM) focusing on features that were newly implemented or further developed during this thesis. Furthermore, this section provides an overview of multi-criteria analysis methods in forest management planning. Findings of this thesis are summarised in Section 1.3 and discussed in Section 1.4, leading to the conclusions in Section 1.5. Finally, Section 1.6 summarises the author's contributions to the individual papers of this thesis.

Chapter 2 summarises the objectives, methods, findings, and difficulties of three scientific stakeholder dialogues conducted at the Potsdam Institute of Climate Impact Research (PIK). This section concerns the dialogue with stakeholders in forestry and forest-related branches on forest management objectives and the impact of climate change on those objectives. Chapter 3 and 4 investigate the impact of management strategies at stand and regional levels on carbon sequestration in forest and wood products, groundwater recharge, biodiversity, and income from timber production under current climate and two climate change scenarios. Furthermore, the priority, with respect to the applied management strategies, are analysed for three stakeholder groups (environmental organisation, private forest owner, and forest manager of public-owned forest). Chapter 5 focuses on the impact of forest management strategies on carbon storage in the wood industry sector plus carbon emission reduction through material and energy substitution along with carbon storage in the forest sector at the management unit level, in Brandenburg, and in Germany. Chapter 5 also includes an uncertainty analysis of the carbon sequestration in the wood industry sector plus substitution effects.

1.2 Methods

1.2.1 Forest growth model 4C

The forest growth model 4C ('FORESEE' - FORESt Ecosystem in a changing Environment) is a process-based physiological model. The model simulates tree species composition, forest structure, forest growth, as well as ecosystem carbon and water balances. Tree growth is modelled using a cohort approach. A tree cohort represents individual trees of the same species, age, and similar size. It is assumed that the site is evenly stocked because the exact position of the individual trees are unknown. The competition of the cohorts for light, water, and nutrients influences their growth, mortality, and the regeneration of the stand. Currently, the model is parameterised for seven tree species: European beech (*Fagus sylvatica* L.), Norway spruce (*Picea abies* L. Karst.), Scots pine (*Pinus sylvestris* L.), oaks (*Quercus robur* L., and *Quercus petraea* Liebl.), European white birch (*Betula pendula* Roth.), Aspen (*Populus tremulus* L.) and Aleppo pine (*Pinus halepensis* Mill.). Different integration steps ranging from daily time steps (e.g. soil dynamics and climate data) and weekly time steps (e.g. net primary production) to annual time steps (e.g. tree demography and management) are used for the various sub-models (Figure 1.1). Detailed descriptions of 4C and its sub-models can be found in Suckow et al. (2001), Schaber and Badeck (2003), Lasch et al. (2005), Freeman et al. (2005), and Thürig et al. (2007).

The simulation of forest growth dynamics, soil water, and soil temperature within 4C were validated against measurements on monitoring sites (Schaber et al. 1999; Mäkelä et al. 2000; Suckow et al. 2001; Lindner et al. 2005). Application areas of 4C are manifold: (i) investigation of forest growth under a changing climate (Bugmann et al. 1997; Lasch et al. 2002; Gerstengarbe et al. 2003; Suckow et al. 2005; Kollas 2007), (ii) the study of effects of management strategies on carbon sequestration in forest and wood product sector including substitution effects, groundwater recharge, biodiversity, and income from timber production (Suckow et al. 2002, Gerstengarbe et al. 2003, Gracia et al. 2005, Lasch et al. 2005, Kollas 2007, Chapter 3, Chapter 4), (iii) the simulation of energy wood plantations on low quality agriculture sites (Rock et al. 2007a,b), (iv) the investigation of forest regeneration after storm events (Brüsch 2002), and (v) investigation of future forest fire risks (Badeck et al. 2004; Suckow et al. 2005).

Forest management

The model 4C enables the simulation of management plans in mono-species stands by combining different thinning, harvesting, and regeneration strategies (as examples see the management plans applied in Chapter 3 and 4 in Table 1.1). The time schedule of tending and thinning in young stands depends on the main tree height and once a height of 15m is attained, thinnings are scheduled in regular time intervals (e.g. every 10 years). Young stands are tended at a mean height of 3 m and 15% to 30% of the trees are cut. Half of the trees are removed from the tallest cohorts and the other half is taken equally from

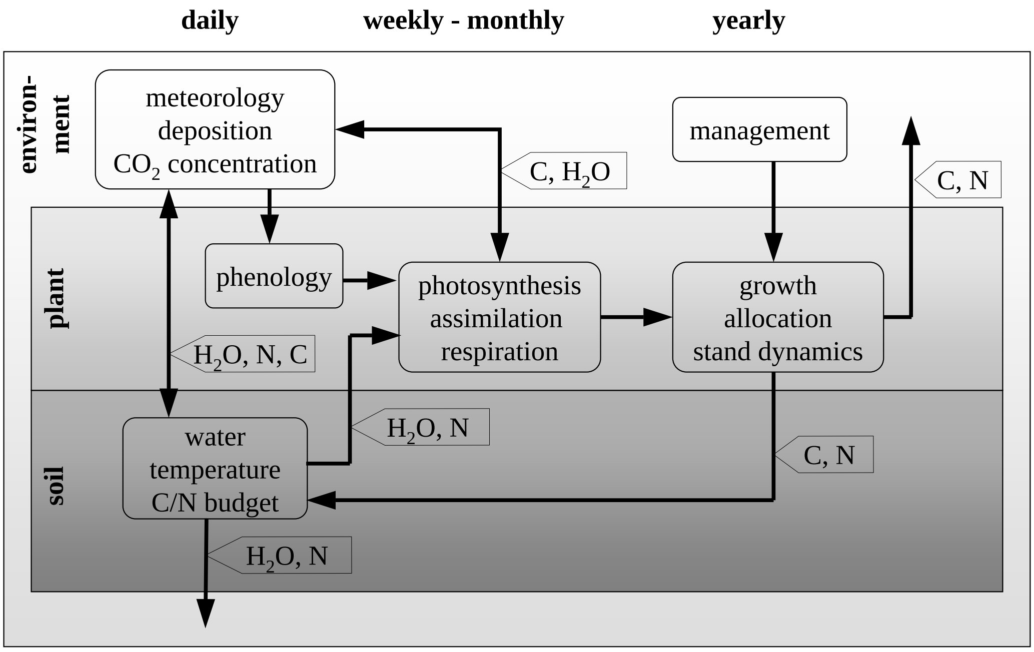


Figure 1.1: Conceptual diagram of the forest growth model 4C.

all cohorts. All compartments of the tended trees remain in the forest and are shifted to the litter pool. During the first thinning, an additional 15% of the trees are cut to model the clearing of skidder trails. Thinning is characterised by the thinning regime and thinning intensity. The thinning regime defines from which section of the stands' diameter distribution trees are removed. 'Thinning from below' removes trees in the lower diameter classes while 'thinning from above' targets trees of high diameter classes. Both methods are modelled by a stochastic approach based on a Weibull-distribution (Gerold 1990, Wenk and Gerold 1996; for further details see Lasch et al. 2005). The thinning intensity can be defined by a target stand density index D_t, usually between 0.7 and 1.0. Based on D_t and the optimal basal area of the stand B_o calculated using species-specific functions communicated by Degenhardt (2001) the thinning aim - the target basal area (B_t) - is determined as the product of B_o and D_t. Features of the thinning such as threshold heights, time intervals, thinning intensity, and thinning regime can be individually adjusted.

4C has the option to chose between two harvesting methods: clear-cut and shelterwood management. The timing of the harvest is defined by the rotation period length which can be chosen individually. Applying the shelterwood system, the stand is opened up in two steps with the aim to allow natural or artificial regeneration and to protect the seedlings against climatic exposure such as frost and extreme heat through the sheltering effect of the old trees. Trees at the lowest 2/3 of the diameter distribution are removed during the regeneration cuts. During the first cut, the basal area is reduced by 30% and seedlings are planted. The second cut removes 40% of the basal area of the old stand and the regeneration is tended. The whole stem of harvested trees is removed from the forest. Branches, foliage, coarse roots, and fine roots remain in the forest and decompose.

The harvested timber can be classified according to the German timber classification system (MELF (Ministerium für Ernährung, Landwirtschaft und Forsten) 1995) for a further socio-economic analysis. Dead stems with a breast height diameter below a certain threshold (e.g. 15 cm) remain in the forest and decompose, while taller dead trees are removed with the next thinning or harvest operation.

Two regeneration methods can be chosen in 4C: natural regeneration and planting. The seedlings are defined by species-specific mean height, minimum value of height, standard deviation of height, and number of seedlings.

Table 1.1: Management plans applied in Chapter 3 and Chapter 4.

Silvicultural operation		Chapter 3	Chapter 4
Tree species		Pine, spruce	Pine, oak
Tending		At a mean tree height of 3m	
Clearing of skidding trail		At a mean tree height of 9m	
Thinning	Schedule	At a mean tree height of 9, 12, 15 m	
		Regular time schedule at a mean tree height higher than 15m	
		10 years	7 or 10 years
	Regime	Thinning from below	Thinning from below in pine stands and thinning from above in oak stands
	Intensity	Defined by target stand density index: 0.7, 0.8 or 0.9	
Harvest	System	Clear-cut	Clear-cut or shelterwood cut
	Rotation period length	80, 120, 160	Pine: 80, 100, 120, 140 Oak: 140, 160, 180
Regeneration	System	With sampling of the same tree species	With sampling of the same tree species or of an alternative tree species
	Saplings	Pine: 10,000 per ha, 2 years old, and mean height 17.5 cm	
		Spruce: 6.000 per ha, 4 years old, and mean height of 37.5 cm	Oak: 9.000 per ha, 2 years old, and mean height of 40.0 cm

1.2.2 Wood product model

The wood product model (WPM) simulates carbon pools and fluxes of wood in the wood products sector and on landfills and the reduction of carbon emissions through material substitution of long-lived wood products and energy substitution (Figure 1.2). The WPM is based on the model concept of carbon accounting in wood products introduced by Karjalainen et al. (1994) and further developed by Eggers (2002), Briceño-Elizondo and Lexer (2004), and Schelhaas et al. (2004).

During this work, the WPM by Eggers (2002) was adapted and further developed for use in 4C. The WPM runs within the forest growth model 4C, but can also be used as a stand-alone model. The WPM requires the annual amount of the harvested timber classified according to the German timber classification system. The pools of the WPM can be initialised by a spin-up run. The WPM comprises four main processes: (i) processing and allocation of carbon in graded timber to wood products, (ii) calculation of the retention period of carbon in wood products and in landfills, (iii) allocation of carbon in wood

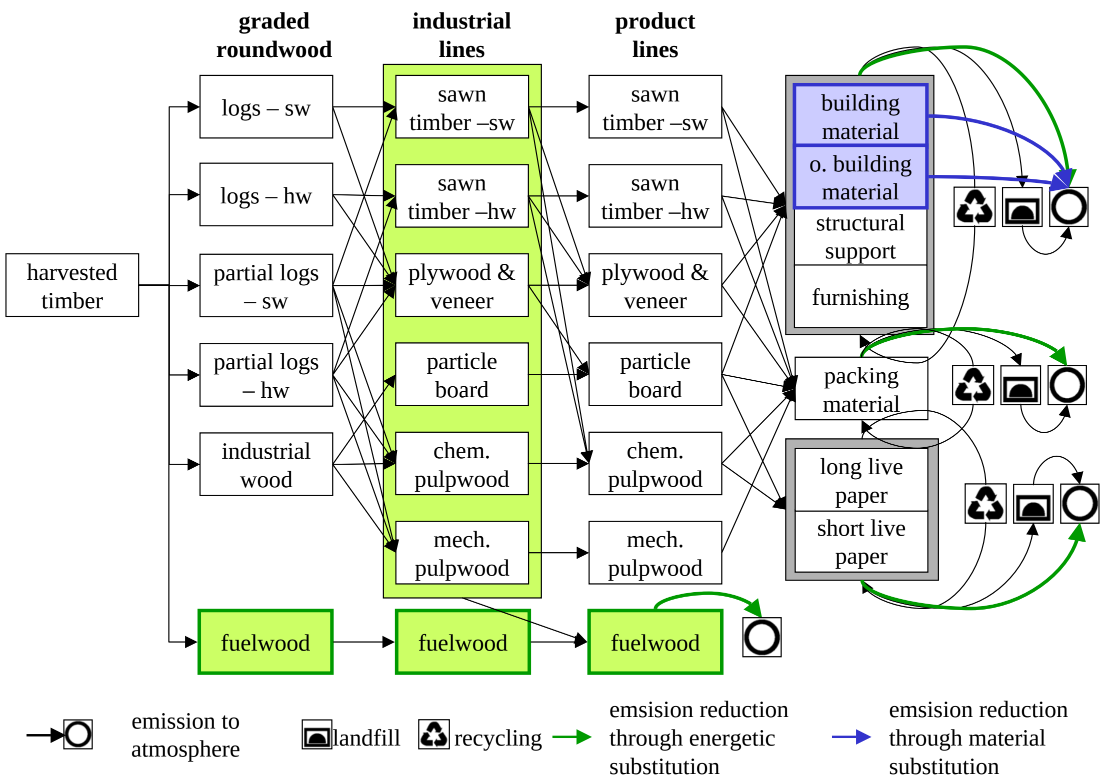


Figure 1.2: Conceptual diagram of the forest wood product model (sw = softwood, hw = hardwood).

products at their end of life to recycling, landfilling or incineration, and (iv) calculation of carbon emission reduction through energy and material substitution.

In the first step, 40% of partial logs and logs are classified as industrial roundwood to account for various timber defects, as based on the experience of forest service personal and literature (LFA (Forstliche Versuchs- und Forschungsanstalt Baden-Württemberg) 1993), if wood quality is not intrinsically modelled in the forest growth model or specified from empirical data. Furthermore, the amount of timber is transferred into carbon with the assumption of 50% carbon in oven dry mass. Carbon in timber grades is distributed into industrial lines based on figures from the German timber market reports 2002 and 2003 (BMVEL (Bundesministerium für Verbraucherschutz, Ernährung und Landwirtschaft) 2003a; 2004a; for the parameters see Appendix B, Table B.6). Seven industrial lines are differentiated and carbon in industrial lines is further distributed into product lines (Figure 1.2). This distribution reflects the processing of timber into main products and by-products and is parameterised according to Eggers (2002). Finally carbon is allocated into use categories. The following use categories are distinguished according to Eggers (2002): building material, other building material, material for structural support, furnishing, packing material, long-life paper, short-life paper. The retention period of carbon in different use categories is defined by a lifespan function, an extended logistic decay function by Row and Phelps (1990). The carbon at the end of the life-cycle of a wood product is removed from the use categories and will, to a certain degree, be recycled, landfilled, or incinerated. Finally, the amount of carbon emission reduced from the atmosphere by material and energy substitution on emission reduction is calculated (for further details see Chapter 5).

1.2.3 Multi-use forest management and multi-criteria analysis methods

Important processes to promote sustainable multi-use forest management

Since the middle of the last century, the demand for the sustainable development of the world's forest ecosystems to maintain and provide diverse functions has become increasingly recognised at international, European, and state levels. At the international level, in 1992 the UNCED (United Nations Conference on Environment and Development) in Rio de Janeiro was a major milestone for the integration of environmental goals in relation to sustainable development in global policies. First steps were already taken in 1972 at the United Nations Conference on the Human Environment. Three of the five major instruments agreed on at UNCED set an international framework for the use of forest ecosystems and underlined the contribution of forestry to the sustainable development of countries. The Forest Principles (formally known as the Non-Legally Binding Authoritative Statement of Principles for a Global Consensus on the Management, Conservation and Sustainable Development of All Types of Forests; DESA (United Nations Department of Economic and Social Affairs) 1992) focused at maintaining the multi-functionality of forest ecosystems to meet social, economic, ecological, cultural, and spiritual needs of present and future generations. The climate protection function of forest ecosystems is addressed in the Framework Convention on Climate Change (FCCC; UN (United Nations) 1992) and the subsequent processes. In 1997 the Kyoto Proctocol was adopted, in 2001 detailed rules for the implementation of the Kyoto Protocol were set by the Marrakesh Accords, and in February 2005 the Kyoto Protocol entered into force committing individual, legally-binding targets of greenhouse gas (GHG) emission. Activities to reduce GHG emission in the forestry sector were defined by Artikel 3.3 (afforestation, reforestation, and deforestation), 3.4 (forest management), and 12 (clean development mechanism). The conservation and maintenance of biological diversity was already a matter of international concern, especially since the Brundtland Report in 1987, and drafts of the Convention on Biological Diversity (CBD; UN (United Nations) 1993) were prepared before UNCED. The issues of the convention were conservation and sustainable use of biological diversity, the regulated access to genetic resources, and a fair and equitable sharing of benefits arising from the use of genetic resources. Following the 1992 UNCED, the World Summit on Sustainable Development was held in 2002 in Johannesburg. Furthermore, at the global level, criteria and indicators of sustainable forest management were developed by intergovernmental processes, e.g. Forest Stewardship Council (FSC) and the Programme for the Endorsement of Forest Certification schemes (PEFC).

At the European level, the Ministerial Conference on the Protection of Forests in Europe (MCPFE) was launched in 1990 addressing the most important issues of forest and forestry. A continuing process of conferences and expert meetings set recommendations in favour of the protection and sustainable management on European forests. The climate protection function by forestry and the use of wood as an energy source and alternative to non-renewable materials are addressed in the Helsinki and Vienna Resolutions (MCPFE (Ministerial Conference on the Protection of Forests in Europe) 1993b; H4, MCPFE (Ministerial Conference on the Protection of Forests in Europe) 2003c; V5). Resolution H2 of the Helsinki Conference calls for a conservation and appropriate enhancement of biological diversity in all types of forests as essential part of forest management (MCPFE (Ministerial Conference on the Protection of Forests in Europe) 1993a). Guidelines to achieve this goal are listed in Resolution V4 of the Vienna Conference (MCPFE (Ministerial Conference on the Protection of Forests in Europe) 2003b). Other existing initiatives and programmes at the European level on nature conservation and biodiversity are the Pan-European Biological and Landscape Diversity Strategy and the Habitats Directive (formally known as Council Directive 92/43/EEC on the Conservation of Natural Habitats and of Wild Fauna and Flora; EU (European Union) (1992)), and the Natura 2000 network. Furthermore, the preservation and enhancement of the social and cultural dimensions of forest management was set as goal (MCPFE (Ministerial Conference on the Protection of Forests in Europe) 2003a; V3).

Germany has a long tradition of sustainable forest management. The German forest law of 1975 lists in Article 1 next to the economic function of the forest, the protective function (e.g. productivity of the ecosystem, climate, water balance, and purification of air pollution) and recreation function. For example, in the Federal State of Brandenburg 90% of the forest serves an economic function, 62% a protective function, and 36% a recreation function (double counting is possible; MLUV (Ministerium für Ländliche Entwicklung, Umwelt und Verbraucherschutz) 2007b). Changes in the overall concept of forest functions and forestry are apparent in the forest laws of the federal states and the negotiation process of the German forest law. Most federal laws have included the protection of fauna and flora as a main goal of forest management under the umbrella of the protective function or as a separate function during the last years. Furthermore, they also do not rank the economic function in the first place or explicitly address the coequality of all forest functions, and they include a definition of sustainable (close-to-nature) forest management with high environmental standards and the abandonment of clearcutting practices. In addition to the forest laws at the state and federal levels different programmes, guidelines, and activities of the forest service contribute to the sustainable maintenance of forest ecosystems and their biological diversity, such as Forestry and Biological Diversity Strategies (BMELF (Bundesministerium für Ernährung, Landwirtschaft und Forsten) 2000a; BMVEL (Bundesministerium für Verbraucherschutz, Ernährung und Landwirtschaft) 2002) and the "Grüner Ordner" (forest guidelines of the Federal State of Brandenburg; MLUR (Ministerium für Landwirtschaft, Umweltschutz und Raumordnung) 2004). As a process following the UNCED, the National Forest Programm (NFP)(later named "Nationales Waldprogramm Deutschland" (NWP)) was initiated in 1999 by the Federal Ministry of Food, Agriculture, and Forestry. The main objective is a continuing dialogue open to all interested forest-related stakeholders groups about future forest use and forest management (BMELF (Bundesministerium für Ernährung, Landwirtschaft und Forsten) 2000b; BMVEL (Bundesministerium für Verbraucherschutz, Ernährung und Landwirtschaft) 2003b, 2004b). The NFP identified the main goals, the need for action, the responsible players, and gave recommendations in the fields of international cooperation in the forest sector and international trade, biodiversity, choice of forest policy instruments, economic relevance of forestry and the wood industry, and the new function(s) of forests (BMVEL (Bundesministerium für Verbraucherschutz, Ernährung und Landwirtschaft) 2003a). A further step to maintain, use and strengthen the multi-functionality of forest ecosystems is a better understanding of processes in the forest ecosystem and the development of new technologies in the forestry and the wood industry. Many research projects are fund by the German Government such as the Agency of Renewable Resources (FNR), the joint projects "Future-oriented Forestry" (1999 - 2004), "Integrated Environmental Protection in the Timber Industry" (1999 - 2004), and "Sustainable Forestry" (2004 - 2008) as well as monitoring programmes such as the Federal Forest Inventory (BWI), soil mapping - "Bodenzustandserhebung im Wald" (BZE), and genetic monitoring.

Multi-criteria analysis methods

Multi-use forestry and often conflicting stakeholder interests call for flexible and versatile methods in strategic forest planning to analyse forest management decisions and are needed due to the long-lasting effects of forest management (e.g. species choice) on economic, ecological and social functions. These methods can be provided by combining forest growth simulation models, socio-economic models, and multi-criteria analysis methods (MCA). Forest planning and the analysis of its consequences include the following steps: (i) acquisition of forest data and frame conditions (e.g. forest law and forest guidelines, predicted future climate conditions, economic restrictions) and evaluation of the actual situation, (ii) assessment of forest management objectives and criteria of decision makers and, eventually, of other interest groups, (iii) selection of appropriate forest management alternatives and analysis of their consequences, (iv) ranking of the alternatives and selecting the best option with respect to the objectives defined in phase (ii) using MCA methods.

MCA methods provide a tool to meet the demands of today's complex forest management as they were developed to deal with difficulties in human decision making while handling complex systems in a consistent way. All MCA techniques have the following features in common: (i) they define an explicit set of objectives of the decision maker, their measurable criteria and decision alternatives, (ii) they require judgements on the priority settings between the decision options according to objectives, (iii) they predict and analyse the consequences of the decision alternatives on the decision criteria and the objectives of the decision maker, (iv) they provide methods to aggregate the data on the individual criteria to provide a measure to select a single most preferred option, to rank options, to select options suitable for subsequent detailed appraisal, or to distinguish between acceptable or unacceptable options. The decision maker can be integrated in the ranking of alternatives and the search for the best suitable solution of the decision problem. The MCA methods will be chosen depending on the question of the specific multi-criteria decision problem, the available information and database, decision makers' involvement, the technical background, and the need of comprehensibility of the MCA methodology and their results for scientists, decision makers, and stakeholders. Application areas of multi-criteria analysis techniques are manifold in forest management planning, some examples are listed in Table 1.2.

Ranking, rating and pairwise comparison are three methods to select and prioritise decision objectives and their criteria. All of them are transparent, easy to understand and offer a convenient environment for participatory decision making (Mendoza and Prabhu 2000b; Sheppard and Meitner 2005). Ranking orders the criteria according to their importance. Rating distributes a given score (e.g. 100 points) among the elements and, in this way, judges their relative importance. Pairwise comparison judges the elements of the decision problem through a one-on-one comparison of their importance. Among these methods, pairwise comparison is found to reflect the most refined priorities of the decision elements, but to be the least comfortable method for decision makers (Mendoza and Prabhu 2000b).

Table 1.2: Example of application areas of MCA methods in forest management planning.

Source	Forest management objectives	Special feature[1]	Region
Kangas (1992)	Timber production, yields of other products, amenity values, benefits from game management, conservation values	1	Finland
Pukkala and Miina (1997)	Profitability, economic security, amenity values	1, 5	Finland
Pykäkläinen et al. (1999)	Income, regional socio-economic values, recreation, nature conservation	2	Finland
Strange et al. (1999)	Timber production, yields of other products, social value of carbon storage, social value of recreation	3	Poland
Lexer (2000)	Timber production, sustainability, and biodiversity	1	Austria
Vacik and Lexer (2001)	Timber production, recreation, protection functions (water, rock fall and avalanches), and biodiversity	3	Austria
Ananda and Herath (2003)	Sawlog production, old-growth conservation, recreation intensity	2	Australia
Huth et al. (2005)	Timber production and forest structure		Malaysia
Sheppard and Meitner (2005)	Biological richness, forest/soil productivity, timber and non-timber economic benefits, water supply, recreation resources, visual quality, cultural features/places, and worker/visitor safety	2, 3, 4	Canada

[1] 1 = risk assessment, 2 = participatory planning, 3 = spatial objectives, 4 = 3D visulisation, 5 = time preference

The most widely used multi-criteria methods include multi-attribute utility theory, outranking theory, goal programming, and the analytic hierarchy process (AHP). The first three methods are briefly outlined, since the focus is on AHP. The multi-attribute utility theory (Keeney and Raiffa 1796) expresses the decision makers overall appraisal of an alternative by a utility index. The utility index is estimated using a multi-attribute utility function, adding the utility of the single decision criteria weighed with respect to the overall objective. Constraints can be added. Outranking represents the French school of multi-criteria analysis methods (Roy 1973). All decision alternatives are compared in pairwise manner, separately for each criterion, on a scale between 0 and 1. The priorities are aggregated over all indicators to calculate the overall priority of each pair of decision alternatives. An important advantage of the outranking methods is that it offers the ability to deal with ordinal and more or less descriptive information. The difficult interpretation of the results is the main weakness of the outranking methods. Two outranking methods commonly used in natural resources management are ELECTRE III and PROMETHEE II (Kangas et al. 2001a; Huth et al. 2005). Goal programming is a modification of linear programming to handle multiple, normally conflicting objectives. Goal programming measures the deviation of the objectives from a given target value and tries to minimise the deviations. Its objective function is expressed in terms of the deviations from the target objectives as a vector or weighted sum. An important advantage of goal programming is its simplicity and ease of use. Furthermore, it is possible to handle large numbers of variables, constraints and objectives.

The analytic hierarchy process

The AHP, originally developed by (Saaty 1977, 1990) consists of four basic steps. First, the decision problem is broken up into subsystems for a better understanding and to study functional interactions of its components and their impact on the entire system. This abstraction of a system structure is called hierarchy. It is assumed that the elements can be grouped in disjoint sets (hierarchical levels) and that the elements of a level influence and are influenced by the elements of only one other level. Because hierarchies can be easily expanded in their complexity, and subsequently become difficult to handle, they have to be built carefully making compromises between being a precise duplicate of the reality and an abstraction of only those elements which are important to solve the research question. The impact of a level on the next adjacent higher level can be evaluated by relative priorities of the elements of that level with respect to the adjacent level. The highest level of the hierarchy must be composed very carefully because these priorities drive the rest of the hierarchy. The hierarchy consists, typically, of at least four levels (Figure 1.3). The first level defines the overall goal of the decision problem; the second level, its partial decision objectives. The partial decision objectives are specified by decision criteria at the third level. Finally, the lowest level contains the decision alternatives to be evaluated. The second and third hierarchical level can be expanded by additional levels to provide further structuring of the decision problem, if necessary.

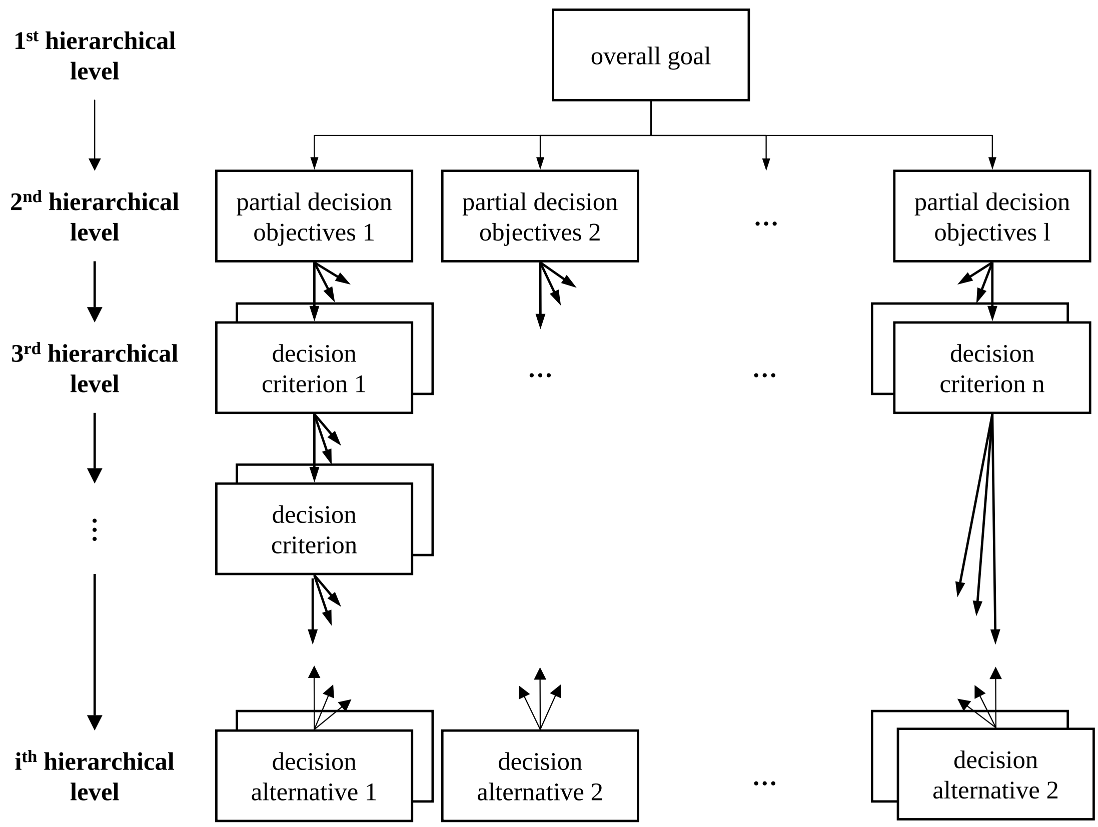


Figure 1.3: The basic structure of a AHP hierarchy.

The second step of the AHP is the pairwise comparison. The elements at each hierarchical level are pairwise compared to determine their preference with respect to the elements of the next higher level. Two elements (C_i and C_j) are compared at a time on a verbal scale of relative importance. The decision maker has the option to express the preference from equal importance to absolute importance of one element over the other. If C_i is equal or more important than C_j, the verbal comparison is transformed into a corresponding numerical score given in Table 1.3. The reciprocal values are used if C_i is less important than C_j. The numbers 2, 4, 6, 8 and their reciprocals can be used to enlarge the scale. This process has the advantage of focusing exclusively on two elements and their relationship one at a time.

Table 1.3: Verbal comparison used in the pairwise comparison and their corresponding numerical score according to Saaty (1977).

Score	Descriptionn
1	Equal importance
3	Weak importance of one over the other
5	Essential or strong importance
7	Demonstrated importance
9	Absolute importance

In the third step, the Eigenvalue method is then used to determine the weights of the partial objectives and the decision criteria. An n-by-n matrix (where n is the number of decision elements) of pairwise comparisons is determined. The principal eigenvector of the matrix is calculated and normalised. The following rules are defined: $a_{ij} = 1/a_{ij}$ and thus, when i = j, $a_{ij} = 1$. Thus the matrix A has the form:

$$A = A_{ij} = \begin{bmatrix} 1 & w_1/w_2 & \dots & w_1/w_n \\ w_2/w_1 & 1 & \dots & w_2/w_n \\ \vdots & \vdots & \vdots & \vdots \\ w_n/w_1 & w_n/w_2 & \dots & 1 \end{bmatrix} \tag{1.1}$$

where w_i/w_j is the preference ratio of the decision elements i and j.

The AHP is a simple and effective method to evaluate multi-criteria decision problems and is therefore suitable for participatory involvement. It forces decision makers and participants to define the objectives of a decision problem and its criteria which can be qualitative and quantitative. Using APH objective information, expert knowledge as well as subjective preference can be included in the analysis. The priority estimation of objectives can be easily interpreted and trade-offs between competing objectives and interests can be illustrated. Applying AHP it has to be kept in mind that the number of comparisons can increase rapidly with the number of criteria and alternatives which may hinder an easy analysis of decision alternatives. The AHP method ifself has no possibility to express hesitations regarding the comparisons and provides no tools to investigate uncertainties based on the original and produced data (Kangas and Kangas 2005).

The AHP was developed for conflict solution in the economic sector in the 1970's (Saaty 2001) and was first proposed as an approach to multiple-objective forest planning by Mendoza and Sprouse (1989). Thereafter, the AHP has been widely used for structuring, analysing and solving forest planning aspects with or without stakeholder integration (e.g. Kangas 1996; Lexer 2000; Schmoldt et al. 2001; Vacik and Lexer 2001). Research related to AHP and its applications has led to methodological advances and extensions. Hybrid methods have been developed to combine the advantages of AHP with the benefits of other MCA approaches such as heuristic optimisation method (HERO; Pukkala and Kangas 1993; 1998; Kangas et al. 2001b), goal programming (Díaz-Balteiro and Romero 2001), linear programming (Kangas 1992; Korhonen and Wallenius 2001), and SWOT (strength-weakness-opportunity-threat; Kurtilla et al. 2000), to fit the demand of decision problem. A further evolution of the AHP is the analytic network process (Saaty 2001; Wolfslehner et al. 2005).

1.3 Results

1.3.1 Science-based stakeholder dialogue

Eleven of 24 local representatives of national and international stakeholder groups closely related to use and management of forest ecosystems services and functions followed up on the invitation to participate in the stakeholder dialogue regarding the impact of climate change on forest functions. Unfortunately, none of the invited representatives of the tourism branch, water management, and the wood industry were able to attend the meeting. Scientists and stakeholders exchanged their specific knowledge and experience on problems induced by climate change for the forest sector and discussed the relevance of the climate change impact on forest management and possibilities to react to changes. Commonly, the opinion that climate change will influence forest ecosystems and forest management was shared. But the individual stakeholders had different views, mainly due to economic constraints, of the necessity to react now to minimise the potential negative impacts of climate change. Forest service personnel and scientists, who are relatively free from economic considerations, were more anxious to find ways to react to climate change in forest management than private forest owners.

The main objectives of forest management defined at the workshop were: timber production, fuelwood production, conservation and increase of biodiversity and semi-natural forest ecosystems, carbon sequestration, groundwater recharge and social functions. The questionnaire used to weight the objectives was returned completely answered by 7 of 11 participants of the stakeholder workshop and by 3 of 23 stakeholders who were also asked to fill in the questionnaire (Appendix A; Figure A.1). Despite the low number of answered questionnaires some conclusions could be drawn from them. Three groups with different objective profiles were distinguished: (i) forest managers of publicly owned forests and climate change scientists (FM), (ii) private forest owners and representatives related to the wood industry (FO), and (iii) environmental organisations (EO). The first group, FM, focused on timber production (Table 1.4). Relatively high priority values were also assigned to biodiversity and close-to-nature forestry, as well as social functions. The second group, FO, prioritised economic objectives (timber or fuelwood production). The representatives of EO (who had a forestry related background) shared the view of forests as ecosystems evenly providing all forest functions, in contrast to a generally expected emphasis on biodiversity and climate protection which was represented by the forest soil scientist. Overall, for half of the representatives, timber production had the highest priority and fuelwood production the lowest. The social function objective had the most controversial ranking - three times the highest priority and three times the lowest priority.

For the case study applications the following objectives were selected: income from timber production, carbon sequestration, biodiversity and groundwater recharge. The impact of management on social functions was not investigated as factors such as infrastructure, leisure facilities, or lakes influence this function more than silvicultural management. The exemplary priority of forest management objectives for one member of each group is shown in Figure 1.4.

Table 1.4: Stakeholder priorities for forest management objectives (dark grey fields mark the objectives with the highest weight and light grey fields with the lowest weight).

Stakeholder	Stakeholder group[1]	Timber production	Fuelwood production	Biodiversity	Carbon sequestration	Groundwater recharge	Social functions
Local forest manager 1	FM	0.36	0.07	0.20	0.03	0.06	0.28
Local forest manager 2	FM	0.30	0.03	0.17	0.08	0.19	0.23
Climate change scientist 1	FM	0.27	0.03	0.22	0.11	0.08	0.28
Climate change scientist 2	FM	0.27	0.04	0.28	0.06	0.10	0.24
Private forest owner (outside of Brandenburg)	FO	0.51	0.23	0.11	0.08	0.04	0.03
Waste wood user	FO	0.20	0.55	0.07	0.05	0.08	0.05
Wood technology scientist	FO	0.45	0.25	0.03	0.12	0.09	0.06
Environmental organisation 1	EO	0.22	0.12	0.15	0.15	0.23	0.12
Environmental organisation 2	EO	0.18	0.03	0.18	0.18	0.15	0.27
Scientist (soil science)		0.15	0.08	0.30	0.08	0.08	0.30

[1]FM = forest manager of public-owned forest, FO = private forest owner, EO = local environmental organisation.

1.3.2 The impact of substituting non-wood products with wood products on carbon emissions and other ecological factors - a literature review

In almost all reviewed studies, the substitution of non-wood products with wood products led to a reduction of carbon and/or GHGs emissions during their life cycle. The effect of this material substitution on carbon ($S_{mat,C}$) and GHG emissions ($S_{mat,GHG}$) was quantified in tonnes of carbon equivalents per tonnes of carbon in used wood (t C (t C)$^{-1}$), where $S_{mat} > 0$ indicates a reduction of the emissions to the atmosphere when wood was used instead of equivalent materials. $S_{mat,C}$ and $S_{mat,GHG}$ of single wood products ranged from -9.8 to 27.1 and -8.1 to 22.5 (Appendix A Table A.1). Smaller ranges were observed if windows were excluded ($S_{mat,C}$: -0.1 to 2.2, $S_{mat,GHG}$: 0.02 to 2.2). The mean values of 10 investigated wood products for $S_{mat,C}$ ranged from 0.1 to 3.6 and for $S_{mat,GHG}$ from 0.2 to 3.8, with the highest mean values for windows followed by the orchard trellis systems (Figure 1.5). The aggregated $S_{mat,C}$ and $S_{mat,GHG}$ of the reviewed studies was 0.71 and 0.90.

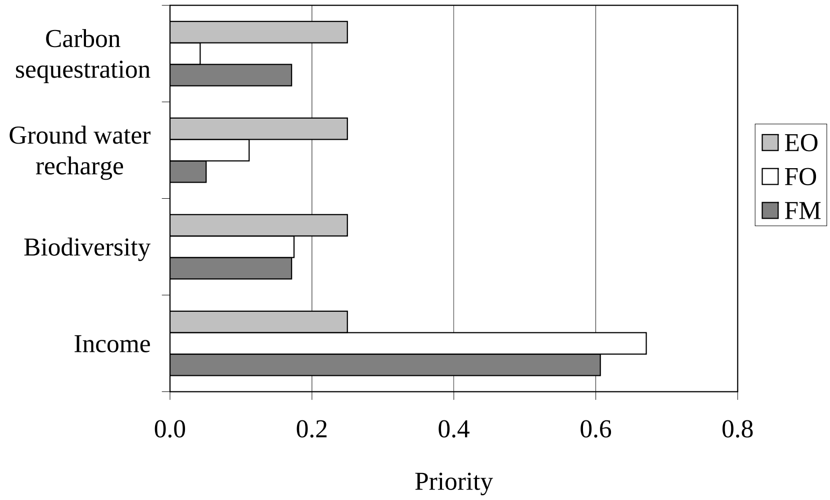


Figure 1.4: Preference of forest management objectives to a local environmental organisation (EO), a private forest owner (FO) and forest manager of public-owned forest (FM).

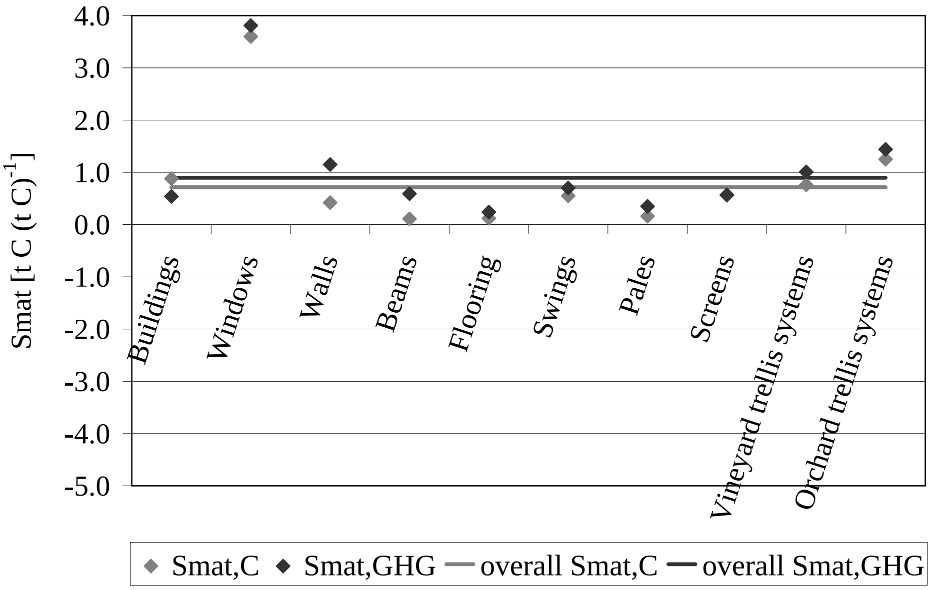


Figure 1.5: Aggregated $S_{mat,C}$ and $S_{mat,GHG}$ of the investigated wood products and the overall $S_{mat,C}$ and $S_{mat,GHG}$ calculated in this study.

Furthermore, wood products were often more preferable than their equivalent products in terms of other ecological factors, such as acidification, nutrification, and photochemical oxidant formation (Appendix A). Two studies also investigated the effect of using wood or other materials on ozone depletion, human toxicity potential, soil toxicity potential, and aquatic toxicity potential during the life cycle of windows (Richter et al. 1996) and exterior constructions (Künniger and Richter 2001). In most cases wood products were less preferable than their equivalent products under these criteria with the exception that wooden windows had a lower aquatic toxicity than windows made of other materials (Appendix A).

1.3.3 The impact of forest management and climate change on forest functions

The section presents the evaluation of the impact of forest management strategies on forest function in three studies (Chapter 3, Chapter 4 and Chapter 5) which were conducted at different scales, partly under different management strategies and with different simulation time intervals. Mean features of the study and abbreviations used in this section are summarised in Table 1.5.

Table 1.5: General characteristics of the studies in Chapter 3, Chapter 4, and Chapter 5.

Study	Scale	Management strategies	Time interval	Abbreviation in this section
Chapter 3	Stand level	STP1 to STP10	100 years	SL1 to SL10
Chapter 4	Management unit level - Kleinsee	MS1 to MS6[1]	100 years	$KL1_{100}$ to $KL6_{100}$
Chapter 5	Management unit level - Kleinsee	KL1 to KL4[1]	50 years	$KL1_{50}$ to $KL4_{50}$
	Brandenburg	BB1 and BB2	50 years	BB1 and BB2
	Germany	GR1 and GR2	50 years	GR1 and GR2

[1]Management strategies MS1 and KL1, MS2 and KL2, MS3 and KL3, and MS4 and KL4 are identical.

The impact of forest management on groundwater recharge, biodiversity, timber production income

Groundwater recharge was unchanged or only slightly influenced by management at stand and management unit levels (182 to 213mm). A positive impact was observed under conservation management ($KL1_{100}$) and an increasing proportion of oak ($KL3_{100}$) at the management unit level (Table 1.6).

Biodiversity was defined as a function of mean dead wood stock alone at stand level and, additionally, by the share of deciduous stands at the management unit level. Dead wood was considerably higher under conservation management than under active management at both levels. In Kleinsee actively managed forests stored, on average, about one fourth of the amount of dead wood compared to forests under conservation. Only small differences were observed among the management strategies (10.1 to 13.1 t C ha^{-1}). Species composition changed, depending on the management strategies, towards an increased ($KL3_{100}$) or decreased ($KL4_{100}$ to $KL6_{100}$) share of deciduous trees.

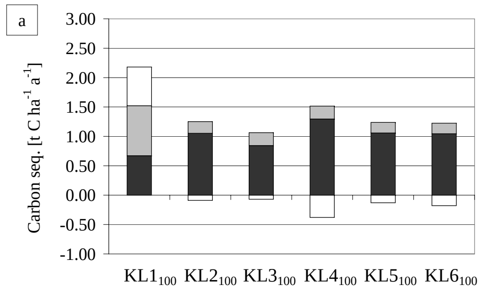
At the stand level, the decision criteria for timber production was mean net increment (mean of sum of harvested and standing timber) over the simulation time. In pine stands, the criteria was influenced by thinning intensity with the highest values under moderate thinning, while in the spruce stand thinning had little impact. The indicators of timber production at the management unit level were main standing stock after 100 years (MST), net present value (NPV), and even flow of income. Under conservation management MST was highest since old stands were over-represented, while no income was achieved. The active management strategies could be split into two groups relative to $KL2_{100}$. Under $KL5_{100}$ and $KL6_{100}$, MST was similar to $KL2_{100}$ while NPV was increased by 45%. The conversion to more oak stands ($KL3_{100}$) and short rotation pine management ($KL4_{100}$) decreased MST (-32% and -17%) and, more so, NPV (-78% and -70%).

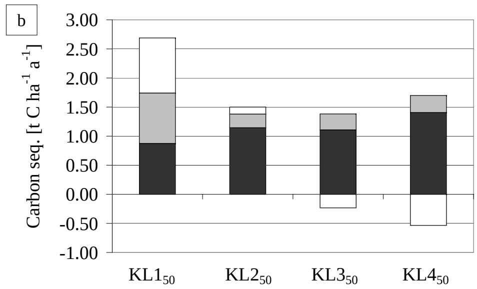
Table 1.6: Values of the decision criteria for the management strategies in the Kleinsee study under current climate scenario and 100 years simulation time.

Decision criteria	$KL1_{100}$	$KL2_{100}$	$KL3_{100}$	$KL4_{100}$	$KL5_{100}$	$KL6_{100}$
Carbon sequestration [t C ha^{-1}]	2.07	1.49	1.24	1.41	1.44	1.37
Percolation [mm]	213	194	203	182	190	190
Dead wood [t C ha^{-1}]	43.3	11.4	12.4	13.1	10.4	10.1
Portion of pine stands [%]	68	68	23	92	83	85
Mean standing stock [m^3 ha^{-1}]	480	238	198	161	237	222
Even flow of income		41	39	19	32	33
NPV [ha^{-1}]	0	979	217	289	1421	1418

The impact of forest management on carbon sequestration in the forest and the wood industry sector including substitution effects

The forest sector Forest soils and dead wood were consistently a carbon sink in all studies independent of the chosen regional scale, management strategy, and time interval. The magnitude of the soil carbon sink and dead wood carbon pool ranged from 0.08 t C ha^{-1} a^{-1} (BB1) to 1.74 t C ha^{-1} a^{-1} ($KL1_{50}$) at regional levels (Figure 1.6a-c). The soil and dead wood pool of EFISCEN simulations was considerably lower than in 4C simulations (Figure 1.6c), partly due to the fact that standing dead wood was not included under EFISCEN. The mean annual carbon sequestration decreased with the prolongation of the time interval from 50 to 100 years in the Kleinsee case. Living forest biomass acted as a carbon sink ($KL2_{100}$ to $KL6_{100}$, $KL3_{50}$, $KL4_{50}$) or carbon source ($KL2_{50}$, BB1, BB2, GR1, GR2) within a range of -0.54 t C ha^{-1} a^{-1} ($KL4_{50}$) to 0.45 t C ha^{-1} a^{-1} (GR1) under management (Figure 1.6a-c). Higher carbon sequestration rates where only found without forest management. The magnitude of the mean annual carbon sequestration in biomass was also influenced by the chosen time interval in the Kleinsee case. Under $KL1_{50}$ and $KL2_{50}$, the mean carbon sequestration was higher than under $KL1_{100}$ and $KL2_{100}$. The opposite effect was observed under $KL3_{50}$ and $KL4_{50}$ compared to $KL3_{100}$ and $KL4_{100}$. The most pronounced influence of a change in management strategy compared to the business as usual ($KL2_{50/100}$) was observed by $KL3_{50/100}$ and $KL4_{50/100}$, while the differences between $KL2_{50/100}$ and $KL5_{50/100}$ and $KL2_{50/100}$ and $KL6_{50/100}$ were small. The main influence of an increased share of oak stands at long terms ($KL3_{100}$), was the reduction in soil carbon. In contrast, the change to exclusively pine in short rotation management ($KL4_{50}$, $KL4_{100}$) lead to the highest increase in soil carbon and highest decrease in carbon sequestration in biomass compared to the other management strategies.





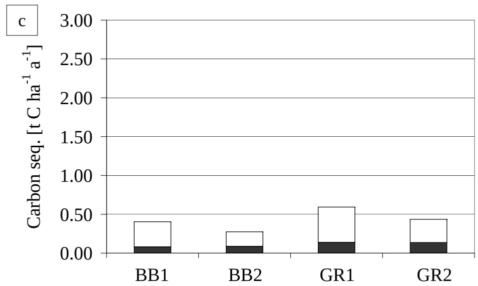


Figure 1.6: Carbon sequestration in the forest sector of the different studies: (a) Kleinsee, 100 years, (b) Kleinsee, 50 years, (c) Brandenburg and Germany, 50 years. Biomass carbon pool is displayed with white, dead wood carbon pool with light gray and soil carbon pool with dark gray.

The wood product sector Mean carbon sequestration in wood products in use and in landfills ranged between 0.26 ($KL3_{100}$) and 0.56 t C ha^{-1} a^{-1} (GR2) under active forest management. Additionally, carbon emissions were reduced by 0.61 (BB1) to 1.04 t C ha^{-1} a^{-1} ($KL4_{50}$) through energy and material substitution. Carbon sequestration and carbon emission reduction in the wood industry sector together, exceeded carbon sequestration in the forest sector (an exception being $KL2_{50}$), in some cases by up to three times. Energy substitution accounted for about half of the total carbon sequestration in the wood industry sector plus substitution effects, followed by landfills (26%), material substitution (14 to 29%), and wood products in use (2 to 14%). The impact of forest management strategies was small on the wood product carbon pools and substitution effects. Without management ($KL1_{50}$), the wood industry sector including substitution effects acted as net carbon source.

Uncertainties of carbon sequestration in the wood industry sector plus substitution effects due to uncertainties in the calculation of $S_{mat,C}$, uncertainties in initialisation time of the spin-up run, uncertainties in future changes in the energy mix and waste management ranged from -11.9% to 6.2% relative to the base scenario (for further details see Chapter 5).

Overall effect of carbon sequestration in the forest and wood product sector including substitution effects The mean annual carbon sequestration in the forestry and the wood industry sectors plus substitution effects ranged from 1.40 (BB2) to 2.77 t C ha^{-1} (KL2$_{50}$). The integration of the substitution effects on the carbon balance lead to a different ranking of the management strategies in Kleinsee than under the sole consideration of carbon pools in the forestry and the wood industry. KL1$_{50}$ no longer achieved the most preferable carbon balance. The highest carbon accumulation plus substitution effects were achieved under KL2$_{50}$, followed by KL4$_{50}$, KL1$_{50}$, and KL3$_{50}$.

In Germany the absolute annual carbon sequestration in the forest and the wood industry sector plus substitution effects was 19.9 Mio t C under GR1 and 19.6 Mio t C under GR2. Energy substitution contributed one third to the total carbon sequestration plus substitution effects. The wood industry sector achieved 70 to 78% of the total carbon sequestration plus substitution effects, 14.02 to 15.27 Mio t C a^{-1}.

The impact of climate change on forest functions

The main impact of climate change scenarios was an enhanced tree growth primarily influencing the partial objectives carbon sequestration and income (Table 1.7). The increase under the dryer ECAHM4 scenario was smaller than under the HadCM2 scenario. Most distinctive was the positive influence of both climate change scenarios among the decision criteria on NPV and among the the management strategies on KL3$_{100}$ (conversion to an oak-dominated forest). The impact of the climate change scenarios on groundwater recharge and dead wood was small under all management strategies (Table 1.7). groundwater recharge mainly decreased, while the dead wood stock slightly increased or decreased depending on the climate change scenario and management strategy. Species distribution was not influenced, due to the fact that the growth conditions under the climate change scenarios were not completely unsuitable for pine or oak. Carbon sequestration in the forest sector and wood product sector was increased under both climate change scenarios.

Table 1.7: Change of the decision criteria under the climate change scenarios ECHAM4 and HadCM2 relative to the current climate scenario in % given separately for KL1$_{100}$ and KL2$_{100}$ to KL6$_{100}$.

Decision criteria	ECHAM4			HadCM2		
		Range			Range	
	KL1	Min	Max	KL1	Min	Max
Carbon sequestration	31.4	12.1	17.3	33.3	21.9	27.4
Percolation	-6.6	-6.5	-5.4	-1.7	-0.2	1.3
Dead wood	-11.8	-1.3	1.8	-2.4	-1.8	3.5
Mean standing stock	49.4	15.5	20.4	27.1	18.1	24.9
NPV	-	27.4	157.1	-	29.1	180.6

1.3.4 Multi-criteria analysis

Two different aspects were evaluated using the multi-criteria analysis technique: the impact of stakeholder priorities and the impact of climate change on the overall utility and ranking of management strategies.

Influence of the priorities of different stakeholder groups

The stakeholder priority setting had the strongest influence on the overall utility of the management strategies at the stand and management unit levels; the focus in this section is on the management unit level. Although the priority setting of FM and FO were not the same, both stakeholders have in common that the overall utility depended strongly on the partial utility from timber production due to the high priority assigned to this objective (to a higher degree for FO than for FM). This resulted in a similar ranking of the management strategies (Figure 1.7a,b). Under $KL5_{100}$ and $KL6_{100}$ the highest overall utilities were obtained. $KL2_{100}$ was ranked third due to the lower partial utility of income from timber production relative to $KL5_{100}$ and $KL6_{100}$ but this was partly offset by the high utility the partial objective biodiversity achieved due to a more preferable species distribution. The application of $KL3_{100}$ and $KL4_{100}$ were less preferable for FM and FO. $KL1_{100}$ achieved the lowest utility. The higher partial utilities of carbon sequestration, groundwater recharge, and biodiversity for $KL1_{100}$ could not compensate for the loss in income from timber production.

The main focus of EO was on a forest management scheme ensuring all forest functions equally. For this priority profile, $KL2_{100}$ provided the highest utility under current climate (0.60) due to higher partial utilities from biodiversity and carbon sequestration compared to strategies $KL3_{100}$ to $KL6_{100}$ (Figure 1.7c). $KL2_{100}$ was closely followed by $KL1_{100}$. The higher partial utilities from carbon sequestration and biodiversity under $KL1_{100}$, compared to $KL2_{100}$, were offset by the partial utility of income from timber production under $KL2_{100}$. The ranking of the other management strategies was: $KL5_{100} > KL6_{100} > KL3_{100} > KL4_{100}$.

The overall utility at stand level for the pole pine and pole spruce stand was maximised under the management strategies with the longest rotation period length, but different thinning regimes.

Influence of climate scenarios

In general, both climate change scenarios (HadCM2 and ECHAM4) increased the overall utility of the management strategies under all stakeholder priority profiles relative to the current climate scenario (CRU), but the effect was stronger under the HadCM2 scenario. The magnitude of the overall utility increase varied among the stakeholder profiles and management strategies. $KL3_{100}$ and $KL4_{100}$ benefited most through a stronger increase of the partial utility of income from timber production than the other management strategies. Under the HadCM2 scenario and the priorities of FM and FO respectively, the ranking of $KL3_{100}$ and $KL4_{100}$ switched relative to CRU but the overall utilities were still very close. The increase of the overall utility of $KL2_{100}$, $KL5_{100}$ and $KL6_{100}$ was small under the climate change and stakeholder scenarios. Under $KL1_{100}$, the increase in the overall utility was mainly due to a strong increase of carbon sequestration in the forest. Thus, the influence of climate change on the overall utility of $KL1_{100}$ is the highest under the priority setting of EO. This led to a change in ranking between $KL1_{100}$ and $KL2_{100}$ compared to the results under the CRU scenario. While $KL2_{100}$ was the most preferable management strategy under the CRU scenario, $KL1_{100}$ was the most preferable management strategy under both climate change scenarios.

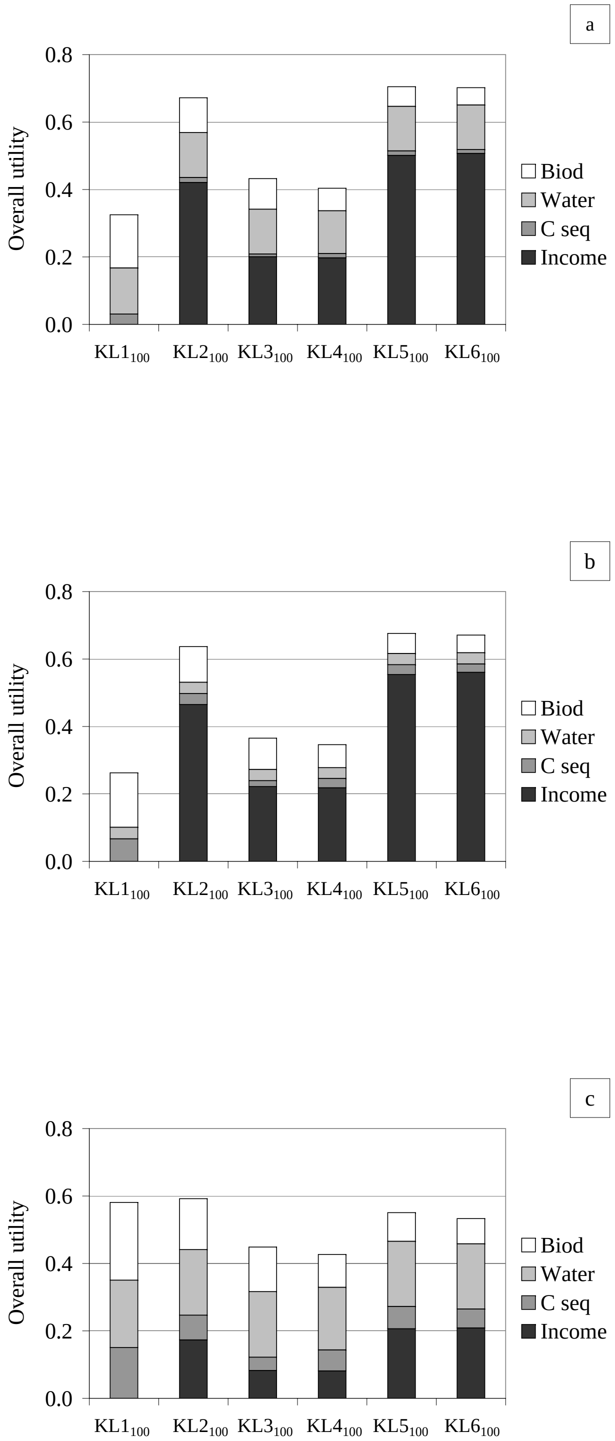


Figure 1.7: Overall utility of stand treatment programs under current climate and the weight of the partial utilities (Biod = biodiversity, Water = groundwater recharge, C seq = carbon sequestration, and income for (a) a forest manager, (b) a forest owner, (c) an environmental organisation.

1.4 Discussion

1.4.1 Science-based stakeholder dialogue

The science-based stakeholder dialogue played a key role in this study and was an effective tool to derive essential information for the regional studies about forest management objectives striven for by different stakeholder groups (Chapter 3 and Chapter 4). In particular, the workshop was found to be very constructive by the stakeholders as well as the project partners. The dialogue helped to understand stakeholders' concerns, problems, restrictions, and uncertainties in current forest management and forest management under the aspect of a changing climate. Since stakeholder dialogues do not focus on achieving a representative sample of the population as public participation, they can provide a wide range of different opinions on a specific topic (Stoll-Kleemann and Welp 2006; Welp and Stoll-Kleemann 2006). Although the full diversity of stakeholders' objectives and priorities could not be investigated due to the absence of representatives from the wood industry, water management, and tourism branch and possible bias induced by the selection of representatives, the tentative assumptions about priority settings of different stakeholder groups were supported by the workshop results. Only the ranking of forest management objectives by the representatives of the environmental organisations was a surprise. Having a forestry background, they considered timber production of equal importance to other functions and did not put a stronger emphasis on conservation. Thus the dialogue between the stakeholders was not as controversial as expected.

1.4.2 The impact of substituting non-wood products with wood products on carbon emissions and other ecological factors - a literature review

With the review of current studies comparing the impact of wood products with similar non-wood products on carbon emission during their life cycle, the estimation factor of carbon emission reduction through material substitution of long-life wood products of earlier studies by Burschel et al. (1993) and Schlamadinger and Marland (1996) could be updated and additional positive effects added. Furthermore, it could be shown that under the aspect of the climate protection function of material substitution it is of interest to analyse their effect on the emission of additional GHGs because the positive effect was increased even further. In addition to the studies reviewed in Chapter 5, other studies were in qualitative agreement with the conclusion that wood products were, in most cases, preferable in terms of reducing carbon dioxide and/or other GHG emissions relative to their equivalent products (Ritsch 1991, Künniger and Richter 1998, Forintek Canada Corp. 1999, Eyerer and Reinhardt 2000, Glover et al. 2002 and some studies cited by Petersen and Solberg 2005, Werner et al. 2005, Werner et al. 2006). But due to the fact that: (i) most studies were not fully comparable because of different system boundaries of the life cycle analysis and additional factors (see Chapter 5) and (ii) studies in application areas of wood products such as furniture, exterior construction (e.g. bridges), and packing material were missing, further substitution studies are needed to close the gap and to identify areas of wood product use that are most suitable to reduce carbon and other GHG emissions. An advanced analysis of the impact of material substitution on other ecological factors as conducted by e.g. Richter et al. (1996), Waltjen et al. (1999) and Künniger and Richter (2001) can prevent a one-sided focus on climate protection by identifying other areas where the wood products may have disadvantages compared to their equivalent product.

1.4.3 The impact of forest management and climate change on forest functions

Given the scope of the study to evaluate the transient effects of management starting from a forest with a given species and age class distribution, variations induced by another status quo may add uncertainties to the evaluation of the different scenarios. Therefore, the results discussed in the next three sections are valid within the study regions and further generalisations have to be drawn carefully.

Comparing management strategies with timber harvest relative to the business as usual in the Kleinsee case study showed that they all have advantages and disadvantages and none of them can be preferred at first sight. An increase in income from timber production was only possible through an increase of pine stands but this conflicted with the preferred species composition, while the other criteria were influenced very little. In contrast, focusing on oak stands increased biodiversity and positively influenced groundwater recharge which will be increasingly more important if, in the future, precipitation decreases as predicted by some climate change scenarios. But these positive effects can only be achieved if the forest owner accepts drastic financial penalties or if forest policy offers instruments to compensate those losses, for example through financial incentives (new guidelines for the private forest sector in Brandenburg are in preparation; MLUV (Ministerium für Ländliche Entwicklung, Umwelt und Verbraucherschutz) 2007a, MLUV (Ministerium für Ländliche Entwicklung, Umwelt und Verbraucherschutz) 2007c). The conversion to short rotation pine management was the only management strategy showing no advantages. But under changed assumptions that distribute more timber to the category of fuelwood and take into account that the fuelwood prices have increased considerably relative to the prices of other assortments since the first evaluation, the climate protection function and the income from timber production under this scenario will be positively influenced. On the other hand, this management strategy should not be applied at large scale under the current forest guidelines, but it can increase forest structure diversity and product diversity at the management unit level. The same holds true for the other management strategies. Combining the strategies at spatial and temporal scales will most likely increase the advantages and minimise the drawbacks.

The main effect of the climate change scenarios and increasing levels of CO_2 was an increased forest ecosystem productivity influencing the forest function carbon sequestration and income from timber production which is in line with earlier studies (e.g. Kellomäki et al. 2000, Kramer and Mohren 2001, Kellomäki et al. 2005, Lindner et al. 2005). Negative effects - a decreasing percolation rate and amount of dead wood - were only small. However, it must be stressed that precipitation scenarios in the east of Germany are subject to high uncertainties, with GCM scenarios including lower precipitation levels as in the applied scenarios which may lead to growth reduction as reported by other studies (Lasch et al. 2002; Gerstengarbe et al. 2003; Lindner et al. 2005). Furthermore, the fact that the climate change scenarios do not predict climatic extreme events and thus losses due to possible drought events, storms and a higher risk of pest outbreaks due to those extreme events there is most likely an overestimation of the ecosystem productivity and therefore carbon sequestration.

1.4.4 Comprehensive analysis of carbon balance in forest and the wood industry sector

Results of the Kleinsee study indicated that ceasing forest management in this forest will exceed managed forests in terms of carbon storage in living and dead biomass for a long time. The effect of carbon sequestration may be overestimated within 4C (Lasch et al. 2005) and other studies predicted an advantage in terms of carbon sequestration of unmanaged forest for a shorter time period (e.g. Wirth et al.). However, the multiple options within the wood industry sector to sequestrate carbon by additional carbon storage in wood products and especially through the reduction of fossil fuel emissions by material and energy substitution, compensated for the lower net accumulation in the forest and could surpass the possibilities of non-managed forests. In addition, the reduction in carbon emissions from fossil fuels due to energy substitution (which exceeded all other options to sequestrate carbon or reduce carbon emission in the forest and the wood industry sector) and material substitution did not represent a saturating sink as does carbon sequestration in non-managed forests. Instead, it was permanently kept up with every consecutive harvest along with the carbon stocks in the forest.

The evaluation of different forest management strategies led to the conclusion: a combined consideration of carbon sequestration and substitution effects shows different rankings of management strategies than the sole consideration (compare results of Chapter 4 and Chapter 5). The studies in Brandenburg and Germany showed that increased forest harvest and, thereby a reduction in the forest biomass carbon pool compared to business as usual can most likely be offset by the subsequent increase of carbon sequestration in the wood industry sector and its substitution effects.

Overall, Germany's forestry and the wood industry could considerably contribute to the GHG reduction goal committed under the Kyoto Protocol if carbon sequestration in forestry and carbon sequestration of the wood product industry plus substitution effects could be fully accounted under the Kyoto Protocol. Under all options, the use of wood for energy production had the greatest potential to influence the GHG balance as also was concluded by Sathre (2006). However, only the management induced changes in carbon sequestration can be partly accounted for under the Kyoto Protocol and the diverse positive effects of harvested wood reducing carbon and GHG emission are not at all favourably accounted for in the forest sector. In order to not favour a management option that increases carbon sequestration in forestry but at the same time reduces the climate protection function of the wood industry sector, policies are needed that provide measures to investigate and quantify the best forest management strategy to sequestrate carbon in forests and the wood industry sector and reduce carbon emissions by substitution effects at the national scale. The forest growth model 4C and the WPM can serve as a tool to study these effects at the stand and regional level. In contrast to other carbon accounting models such as CO2FIX (Masera et al. 2003; Schelhaas et al. 2004), FULLCAM, and GORCAM (Schlamadinger and Marland 1996) that use empirical growth models and therefore are not able to cope with environmental changes, the application of 4C offers the additional possibility to investigate the impact of changing climatic conditions and increasing CO_2 levels on carbon sequestration in the forest and the wood industry sector plus substitution effects.

1.4.5 Multi-criteria analysis

In this thesis, MCA provided an effective tool to support and evaluate the silvicultural decision process in the search for the most preferable management strategy given a complex set of management objectives, stakeholder interests, and management strategies. Alternative management strategies were compared on the basis of the overall utility. Similarities and differences in the prioritising of a management strategy, the ranking, and the impact of the single management objectives on the overall utility of the management were evaluated. As expected, different management strategies were prioritised by the stakeholders, but under the given conditions a compromise in forest management between the stakeholder groups seems possible. Business as usual combines a high timber production, carbon sequestration, and biodiversity and therefore was the most preferable management alternative under the current climate scenario for EO, while FM and FO would have to accept a small cut back since the management regimes with a higher income achieved a slightly higher overall utility. One way to balance this trade-off for FM or FO could be an adjustment payment for providing a higher biodiversity, increasing the NPV of the simulation period. Another option to meet the expectations of all stakeholder groups could be a mix of different management strategies at the management unit level as is typical in forest management practice.

1.5 Conclusion

This study provides an extensive model-based evaluation of the impact of forest management strategies on different forest functions with the main focus on carbon sequestration in forestry and the wood industry sector including material and energy substitution effects. The priority setting among the management strategies have been investigated for three different stakeholder groups using current and future climate scenarios. The major findings of this study are:

Research increasingly takes place in small interdisciplinary teams. The science-based stakeholder dialogue offers a valuable extension of this practise by bringing together even more specific and diverse knowledge, including a link to real life/ business in science and an increasing acceptance and usability of research results for the stakeholders.

Single forest management objectives can be positively influenced by choosing adequate management strategies. However, this entails a trade-off for other forest functions. To increase advantages and decrease disadvantages of management on forest functions, different alternatives should be combined at local and temporal scales.

The use of wood products, instead of products made of other materials, offers in almost all investigated application areas the possibility to reduce carbon emissions during their life cycle. On average for each tonne of dry wood used in a wood product substituting a non-wood product, 0.71 tonnes less of fossil carbon are emitted into to the atmosphere. Including other GHGs, the climate protection effect of material substitution is even more pronounced.

The main impact of climate change under the given climate change scenarios is an increase in forest ecosystem productivity that positively influences carbon sequestration and income. Negative impacts are only small; however, studies using other climate change scenarios indicate that ecosystem productivity could also decrease in Brandenburg in the future.

The study indicates that for an overall evaluation of the impact of forest management strategies on the climate protection function of forest ecosystems, a combined analysis of the forest and the wood industry sector plus substitution effects is necessary. Under the combined analysis non-managed forests are not further favoured over managed forest in terms of climate protection.

The combination of process-based forest ecosystem models and MCA methods is an efficient tool to support planning and decision making of forest management under current and climate change conditions.

Further Research

In the forests of the Federal State of Brandenburg, many of the predominant coniferous (e.g. Scots pine) forests are currently being transformed into mixed forest stands (Müller 2000) with the aim to increase the portion of mixed stands from 11% to 41% (Roß and Müller 2006). Therefore, the simulation of growth and management of mixed stands should be further developed and evaluated to provide a tool to investigate the effects of conversion of monoculture stands to mixed stands on forest functions and to provide results to support the assumption that under many aspects mixed forests are preferable to monoculture forests.

To further increase the accuracy of the simulated carbon sequestration in forests by 4C, the processes in the soil carbon pool and the carbon sequestration in old stands should be further developed due to uncertainties in these areas (Thürig et al. 2007; Lasch et al. 2005). Additionally, the parameterisation of the WPM needs continual actualisation due to changes in the timber flow in the wood industry sector, changing framing conditions such as the energy mix, new scientific results on the still highly uncertain decay rates of wood on landfills and the life span of wood products in use, and new results of life cycle analysis of wood products and their equivalent products on carbon emission reduction.

Another point of interest is a comprehensive analysis on the overall effect of GHGs sequestration plus substitution effects in the wood product sector. Studies by Schwaiger and Schlamadinger (1998) and Dones et al. (2003) indicate that the positive effect of energy substitution will increase if additional GHGs are taken into consideration. The landfill pool will act as a GHG source if methane emissions are considered in addition to carbon sequestration (Kohlmaier et al. 2007).

Including substitution effects in the evaluation of the climate protection functions of forest ecosystems and wood industry lead to a different ranking of the management strategies. Subsequently, the effect of this change on the priority setting among management strategies should be evaluated under current climate and changing climatic conditions using the MCA method.

1.6 The author's contribution to the individual papers of this thesis

Paper 1 (Chapter 2) This paper is based on a discussion about experiences in scientific stakeholder dialogues at the PIK that I had with Martin Welp and Anne C. de la Vega-Leinert in 2003. I mainly contributed to the book section the experience with stakeholders within the project SILVISTRAT.

Paper 2 (Chapter 3) For this paper I prepared and analysed the questioning of the stakeholders about their objectives with regards to forest functions and the weighting of the forest functions. I also prepared the input data needed for the MCA, contributed to the design of the simulation runs, and to the analysis and interpretation of the results and the discussion.

Paper 3 (Chapter 4) I prepared, analysed, and processed the forest inventory data for this paper, designed and ran the experiments, adapted the MCA method for this research question, and developed a code to run the MCA. Furthermore, I analysed and interpreted the results and drafted several versions of this manuscript. Manfred Lexer contributed to the development of the MCA and to the interpretation of their results. Petra Lasch and Felicitas Suckow helped with the parameterisation of the soil data and management options within 4C. Franz Badeck guided the whole process.

Paper 4 (Chapter 5) I prepared and conducted the literature search for parameters on material and energy substitution, developed the modelling protocols, and did the relevant coding within the WPM. I performed the simulations with 4C and the WPM, did the post-processing and interpretation of the results. Helpful comments on methods, results and discussion were contributed by all co-authors. The data of the EFISCEN simulation and information about the model were provided by Hans Verkerk. I also drafted the several versions of the manuscript.

Chapter 2

Science-based stakeholder dialogues in climate change research

Martin Welp[1], Anne C. de la Vega-Leinert[2], Susanne Stoll-Kleemann[3], Cornelia Fürstenau[2]

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2.1 Introduction

Science-based stakeholder dialogues are structured communication processes linking scientists with societal actors that are relevant for the research problem at hand. Rather than being objects of research, the stakeholders are partners in dialogues, in which the exchange of arguments is the distinguishing feature. The richness and relevance of such dialogues usually increases if there is a safe space in which a broad range of view-points can be freely expressed. Scientists have started to create forums which provide a platform for such interaction and consciously seek dialogues by organising workshops or by launching joint research projects. Science-based stakeholder dialogues can be regarded as a distinct approach to knowledge creation, in which researchers actively seek to incorporate non-scientific knowledge in the research process.

Different streams of literature implicitly or explicitly deal with science-based stakeholder dialogues. Post-normal science, transdisciplinary research and 'Mode 2' knowledge production are the most prominent approaches addressing the need for more stakeholder involvement, each emphasising different aspects of dialogues. The concept of post-normal science developed by Funtowicz and Ravetz (1993) can be characterised as science where the traditional fact/value dichotomy can not be maintained. This line of literature is

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therefore relevant for what will be outlined in this chapter. We speak of post-normal-science when “facts are uncertain, values in dispute, stakes high and decisions are urgent” Funtowicz and Ravetz (1993). Under the conditions of ‘soft’ facts, hard value-related decisions must be made. This requires the involvement of non-scientific knowledge. In this context Hage et al. (2005) see quality assurance as one of the major challenges of post-normal science. To address this challenge Funtowicz and Ravetz suggest ‘extended peer communities’, who “deploy ‘extended facts’ and take an active part in the solution of their problems” Ravetz (1999). Participants of these ‘extended peer communities’ can be all kind of stakeholders from the business, policy or NGO world. Each group can enrich the research process with their local, environmental or sectoral knowledge.

In transdisciplinary research issues are addressed from more than one viewpoint simultaneously (Pohl 2005). To solve complex problems, such as biodiversity loss or climate change a traditional disciplinary approach is not enough. But the line of argumentation goes beyond this: besides different disciplines researching together, research needs to take into account the knowledge outside the scientific sphere. Research will be socially relevant only if the traditional ways knowledge is produced and organised change. One line of interdisciplinary research for example concerns the collaboration between research institutes and industry/the private sector - an issue which is of high relevance for science-based stakeholder dialogues.

Mode 2 knowledge production described by Gibbons et al. (1994) also emphasises transdisciplinarity. The authors observe a shift in those organisations that produce knowledge away from established institutions towards more heterogeneity and reflexivity. Mode 2 knowledge production implies that dialogues play an increasingly important role in critically scrutinising arguments presented by different organisations. A common nominator for the three above-mentioned lines of literature is viewing research as a process of mutual learning. Science-based stakeholder dialogues are part of the practices that have been described as transdisciplinarity, Mode 2 knowledge production or post-normal science.

From the scientists’ point of view relevant stakeholders in a research process may include representatives of the private sector, NGOs, governments, citizen groups or lay persons (Welp et al. 2006). The main difference between using traditional social science approaches (such as interviews or questionnaires) and facilitating science-based stakeholder dialogues is that the latter fosters participatory and collaborative research and promotes mutual learning between all actors involved.

The objectives of science-based stakeholder dialogues may include some of the following: identifying socially relevant research questions, providing a ‘reality check’, incorporating ethical and value considerations in assessments, and accessing stakeholders’ knowledge.

A research process should ideally include several iterations of dialogues, which take place over a long period of time. Different stages may have different objectives. Cycles of stakeholder dialogues may start with identifying relevant research questions and move on to phases of consultation, developing models, reviewing and modifying these models and coming to new conclusions.

There are few recipes to guarantee a successful stakeholder dialogue. The degree of stakeholder involvement, its timing and iteration, and the methods to collect and analyse knowledge uncovered and produced during dialogues are critical aspects to consider. Each research project is designed and run according to its specific research objectives, participants, available resources, etc. Science-based stakeholder dialogues are as diverse as the research questions they explore. Each dialogue is thus a unique process, which will yield unique results. This uniqueness however does not mean that valuable scientific insights and useable qualitative and quantitative knowledge cannot be systematically produced, discussed and tested in stakeholder dialogues. On the contrary, the authors strongly believe that such dialogues substantially increase the social relevance of research and improve the quality of results, provided they are adequately thought out and conducted.

Participation in decision-making has been hailed as one of the pillars of sustainable development and integrated resources management. It has thus been advocated as a means to improve the relevance, legitimacy and implementation of decisions taken, as well as the credibility and accountability of decision makers with regard to civil society. The same principles are increasingly applied to climate change research, which is to a large extent funded by tax-payers via government bodies under the understanding that science has a role to play in informing and guiding society along the path of sustainability transition.

The present paper reflects on stakeholder dialogues and experiences made at the Potsdam Institute for Climate Impact Research (PIK, Germany[1]). PIK conducts integrated assessment projects in the field of adaptation and mitigation of climate change. Most projects have a strong focus on computer modelling of global change, on its potential impacts and possible adaptation. We have selected three initiatives and projects with a particularly strong stakeholder component for further analysis.

In more general terms this paper explores how science-based stakeholder dialogue can play an important role in the generation of knowledge and what the relevance of such dialogues is for the wider society. To this end two objectives are set. First, key aspects relevant to stakeholder dialogues are discussed in the light of the examples and lessons are drawn from an evaluation of PIK's stakeholder experience. Second, theoretical considerations introduced in Welp and Stoll-Kleemann (2006) and extended in Stoll-Kleemann and Welp (2006)are revisited in the light of the practice in science-stakeholder dialogues commented below.

2.2 Stakeholder dialogues in climate change research

2.2.1 Experiences at PIK

PIK has in the last decade played a significant role in climate change research, particularly in model-based integrated assessment studies. It has sought to develop a holistic approach for climate change and climate impact studies, with horizontal integration (via interdisciplinary staff and projects), and vertical integration (via the consideration of all major research aspects from problem formulation to recommendations to policy-makers). At the core of PIK's mission is the wish to produce meaningful insights and to encourage a transition to sustainability.

PIK's mission, research focus and structure have constituted a suitable environment within which science-based stakeholder dialogues have found a natural place. The authors of the present paper have all been involved in innovative participatory environmental research, in particular via stakeholder dialogues. The dialogue initiatives considered here range from the creation of platforms for dialogues, such as associations and forums, to individual projects funded by different sources (EU, national research funding, private companies).

The three selected examples are the European Climate Forum (ECF)[2], ATEAM[3], and

[1]See the PIK web site: www.pik-potsdam.de

[2]See the ECF web site: www.european-climate-forum.net

[3]The full name of the project is Advanced Terrestrial Ecosystem Assessment and Modeling, Project number: EVK2-2000-00075, funded by the 5th Framework Programme of the European Commission un-

SilviStrat[4] (see Table 2.1). ECF is a platform for the exchange of arguments regarding long-term climate policy and other controversial issues related to climate mitigation and adaptation. ATEAM (2001-2003) was concerned with ecosystem service provision and European vulnerability to global change and SilviStrat (2001-2004) with local forest management responses to global change (in the state of Brandenburg, Germany). The above examples are representative of the diversity of stakeholder initiatives at PIK (for further examples see de la Vega-Leinert et al. 2006, in review). While ECF is consolidating a long-term stakeholder process, ATEAM and many other projects run over 3-5 years only. While the research agenda in ECF is responsive to stakeholders' expectations, ATEAM and SilviStrat are product-oriented projects which thus have a well-set agenda defined to a large extent at the project proposal stage.

The stakeholders involved in PIK's stakeholder activities have been diverse, ranging from interested individuals to international corporations. Creating bridges for long-term collaboration between scientists and stakeholders requires intensive attention. Researchers need to be aware that stakeholders may become weary of being approached repeatedly for different activities. To avoid overlaps a PIK stakeholder database was created. This improved communication with various stakeholder groups and facilitated synergies between different projects. In the following the objectives, main issues and involved stakeholders of each case are described.

2.2.2 European Climate Forum (ECF)

The European Climate Forum (ECF) is a non-profit organisation established in 2001 by seven leading research institutions in the field of climate research, energy research and integrated assessment as well as diverse members, which include traditional and renewable energy industries and companies, major energy users, insurance and finance, policy-makers, environmental NGOs, and scientists. Strategic decisions are made in monthly telephone conferences of the board, which includes both scientists and stakeholders.

ECF provides a platform for discussions on controversial climate change issues. The objectives of stakeholder dialogues have ranged from identifying new research questions to combining ethical and factual arguments and accessing stakeholders' local knowledge with respect to impacts of climate change. ECF has focused on issues, for which there exists at present strong disagreement and controversy. Examples of such controversial issues include carbon capturing and storage (CCS), long-term climate policies (Hasselmann et al. 2003), the role of biofuels in the transport sector (ECF (European Climate Forum) 2003), and the question "What is dangerous climate change?"[5] (ECF (European Climate Forum) 2004). Such questions have typically been discussed in the annual ECF events or a thematic workshop.

A further way of cooperating with stakeholders is to initiate and carry out joint studies. An example of close collaboration between researchers and stakeholders was a project on

der the topic "Energy, Environment and Sustainable Development". See the web site: http://www.pik-potsdam.de/ateam/

[4]The full name of the project is Silvicultural Response Strategies to Climate Change in Management of European Forests. See the web site: http://www.efi.fi/projects/silvistrat/

[5]According to the UN Framework Convention on Climate Change the ultimate objective of climate policy is to "stabilise greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system". There is however no agreement what warming levels qualify as dangerous according to this piece of international law. Some stakeholders consider the already observed changes of 0.8°Celsius above pre-industrial levels as dangerous, while others suggest that a 2 °Celsius increase in global mean temperature over a long period of time would have dangerous impacts on ecosystems and human livelihoods (ECF (European Climate Forum) 2004).

videoconferencing with the Deutsche Telekom. The project, which was carried out jointly by PIK and the Deutsche Telekom AG under the umbrella of ECF assessed the potentials of information and communication technologies (ICT) to contribute to a more sustainable development of the transport sector. The focus was on the potential of substituting business travel by using video- or teleconferencing (Runge and Reusswig 2004).

Stakeholders who are involved in ECF activities include the founding members, members who have joined the forum later and invited guests. The stakeholders typically include representatives from corporations and companies operating in sectors such as insurance, car manufacturing, and energy. Also small and medium-sized enterprises (SMEs) and non-governmental organisations (NGOs) such as WWF are involved.

Since the involved individuals and institutions have very different perceptions on the climate change problem, there are differences in the preferred course of action to mitigate and to adapt to climate change. The members have different areas of competence too. For example some have technical know-how, others are strong in economic analysis, while others have data which is of high relevance for integrated assessment studies. These particular competencies combined with the richness of perspectives make the dialogues attractive for both researchers and stakeholders.

The selection of participants has been based on personal contacts rather than on a systematic approach. The group of potential participants to be approached for specific events depends on the issues to be discussed. For example, for the event focusing on biofuels in road transport both energy suppliers, energy distributors and policy-makers were taken into account. The involved NGOs were mainly environmental organisations. Other groups representing sections of civil society, such as consumer and car drivers' associations are interesting as potential future members. It should be noted that policy-makers have been invited to ECF events as guests. Membership is not open to political or government organisations. This is a conscious choice and reflects the view that ECF should be independent from political bodies. Some argue that funding from private businesses may corrode scientific independence as well. Experience has however shown that in such funding arrangements scientific freedom has not been more limited than with public funding sources, in particular since NGOs play a balancing role in the dialogues.

2.2.3 ATEAM

ATEAM was a large interdisciplinary (> 60 scientists) project funded under the 5th EU Framework Programme (Schröter et al. 2005). Its focus was on ecosystem modelling and vulnerability assessment to global change at European scale. The research in ATEAM was not stakeholder-centred, in that it was neither initiated nor run in close collaboration with stakeholders. However, the research process and content throughout the project continuously focused on producing results which could be of use to the stakeholder community targeted by ATEAM. Stakeholders could significantly influence, but not fundamentally change the research work plan, the modelling framework or methodologies developed within the project without stakeholder consultation. The direct role of stakeholders within the project was punctual, mostly feedback orientated, and focused on evaluating specific modelling components as well as the overall scientific results. Stakeholders were involved at key points during the research process, in between which scientists improved and tested their models with consideration of stakeholders' suggestions. The research agenda in ATEAM was further centred on top-down quantification in a natural science context, rather than exploratory bottom-up qualitative research, as for example in the scenario development part of the Millennium Ecosystem Assessment[6]. It was comparable in its aims and process to the dialogue developed within the Delft process (van Daalen et al. 1996).

The goals of the ATEAM stakeholder dialogues were manifold. In particular the project aimed at: 1) opening up the ecological modelling world to a wider audience, 2) fostering greater knowledge integration through inter- and transdisciplinarity, 3) learning from stakeholders what scientific information is meaningful for natural resource managers and decision-makers, 4) improving and evaluating ecosystem service modelling and vulnerability assessment, and 5) raising awareness on global change issues.

The issues ATEAM focused on were: 1) improving modelling of ecosystem service provision under global change, 2) developing a multi-scenario approach (including climate, nitrogen and land use scenarios), 3) producing a preliminary aggregated indicator for adaptive capacity at sub-national level, and 4) combining the above elements innovatively to produce maps of European vulnerability to global change over 4 time slices till 2100. These maps, as well as their interpretation were ATEAM's main deliverables. ATEAM's strong points were thus: its state-of-the-art natural science and terrestrial ecological modelling, for which it has obtained high scientific recognition and credibility, and its willingness to create bridges of collaboration and meaning to social sciences modelling and to a wide range of stakeholders.

ATEAM's stakeholders included public and private sector consultancies (e.g. DHI Water and Environment or Associazione Cultura Turismo Ambiente), sectoral representatives (e.g. cereal growers, paper-agro industries), private businesses (e.g. land and forest owners), public organisations which act as advisers (e.g. European Environmental Agency), managers (e.g. forest, water and or natural park management), non governmental organisations (e.g. Royal Society for the Protection of Birds), independent umbrella organisations (e.g. Comité International pour la Protection des Alpes) and other scientific institutions not involved in the ATEAM consortium.

ATEAM aimed at developing participative methods and activities, and to obtain feedback to improve the usability of its model outputs. It was thus important to collaborate with stakeholders who understood sectoral as well as scientific issues related to global change. Stakeholders' scientific affinity and competence eased the discussion with ATEAM scientists, who especially at the beginning of the project were relatively inexperienced with, and critical of, the dialogue concept. Often stakeholders had different hats (e.g. private sector consultant and academic), and participated as individuals, rather than official representatives of specific organisations. Initially stakeholders from personal networks were invited. Then a matrix was designed with relevant sectors vs. geographical focuses/scales and organisation type. The aim was to systematically produce a sample/database of stakeholders to contact and hopefully involve during the course of the project. Few stakeholders with a purely local focus (e.g. regional nature park managers) were approached since the project was producing limited meaningful results at this scale.

Despite the participation of many stakeholders who represented private sector activities, ATEAM did not sample comprehensively purely commercial interests. ATEAM often targeted environmental managers and consultants who had a green bias, despite keeping in mind at all times the requirements for sectoral competition and market viability. They provided a fresh, albeit controversial (from the point of view of ATEAM scientists) view of the realities of many businesses. Noticeably absent from the spectrum of ATEAM participants were representatives from the transport or financial/insurance sectors, farm-

[6]See: www.millenniumassessment.org.

ers, consumer and/or citizen associations, or downstream manufacturing or distributing activities such as the agro-chemical industry and food processing (except for paper, and energy and water distribution). Contacts were made to fill some of these gaps (e.g. IKEA, Gerling Reinsurance, local farmer(s) and national farmer's association). Non-attendance was then mostly due to the lack of relevance of ATEAM's results for specific commercial activities, of time, or of remuneration (i.e. the project could not cover all expenses, e.g. consultants' fees).

2.2.4 SilviStrat

SilviStrat was also an EU 5th Framework Programme funded research project with 7 partners spread over the different forest regions in Europe from the Mediterranean to the Boreal region. The main focus of the project was to investigate adaptive management strategies to enhance carbon sequestration in European forests and to find ways to mitigate adverse impacts of global climate change. The assessment at a scale of forest management units (Badeck et al. 2005) was based on simulations performed with two forest growth models, 4C (Lasch et al. 2002) and FINNFOR (Kellomäki et al. 1993). Furthermore a wood product model (Eggers 2002) was used to calculate/simulate the fate of carbon in wood products and landfills. The stakeholder dialogue was part of a subproject - a regional study, which evaluated the effects of forest management on forest functions in Brandenburg, Germany.

The overall objective of the stakeholder dialogues within SilviStrat was to investigate forest management objectives and management preferences assigned by single stakeholders. A further objective was to present first relevant findings about the impact of management and climate change on carbon storage and timber production. The effects of global climate change to forest ecosystems and their functions, and the awareness to and relevance of these impacts were discussed and possibilities to react to changes were compiled. The workshop had the aim to bring together scientists and stakeholders to exchange knowledge and experience, discuss the problems of climate change for the forestry sector and define new research questions.

SilviStrat analysed direct and indirect impacts of present forest management operations and climate on carbon sequestration, timber production, biodiversity, and groundwater recharge in European forests. The aim was to develop a better understanding of how management could be improved to maintain sustainable forest production and increase carbon sequestration capacity, and sustain multi-functionality of forest ecosystems under current and changing climate conditions. Additionally, costs and benefits of adaptive management strategies were assessed at the management unit level. In representative management units of major east German forest types the impact of forest operations were simulated with the goal of increasing carbon sequestration, maintaining sustainable forest production and other forest functions under changing climatic conditions. Furthermore the impact of forest management on reduction of drought risk and the potential of forest management for carbon sequestration and mitigation of climate-change-induced impacts was estimated at the European scale.

SilviStrat focused on local stakeholders using goods and services provided by forest ecosystems or managing forest ecosystems, including private forest owners, local environmental organisations, federal forest services (from local forester to higher administrative levels), the wood industry, scientists as well as representatives of forest-related business sectors (water management, tourism).

Table 2.1: Project description.

Project/ initiative	European Climate Forum ECF	ATEAM	SilviStrat
Research focus	- long-term climate policie - energy systems - what is dangerous climate change?	- ecosystem service modelling - European vulnerability assessment	- forest management strategies to mitigate the impacts of climate change - management strategies to enhance carbon sequestration - multi-functional forest management
Dialogue objectives	- new research questions - joint projects	- evaluation of modelling components, scenarios and results - evaluation of sectoral adaptive capacity	- research questions - forest functions and their ranking
Types of stakeholders	- private companies - NGOs - policy-makers - scientists	- private land and forest owners - sectoral representatives - private and public environmental resource managers and consultants - NGOs - scientists	-private forest owners - employees of national forestservices - wood industry - scientists - forest related business sectors (e.g. tourism, water)
Methods	- joint studies - conferences - workshops - scientists - working groups - teleconferences	- workshops - questionnaires - interviews	- workshops - questionnaires - interviews - wood industry
Types of involvement	- exchange of arguments - stakeholders influence the research focus	- influencing case studies and indicators modelled - influencing the presentation of results - help shape future research agenda	- defining forest management objectives - ranking the objectives according to stakeholders' preferences
Deliverables	- discussion papers - conference reports - climate games - model coupling tools	Evaluation of: - modelling indicators - sectoral driving forces - land use scenarios - vulnerability mapping methods and results - dialogue activities	- modelling the impact of different management and climate scenarios on forest functions - evaluating trade-off effects between conflicting management objectives

The regional study within SilviStrat tried to involve mainly representatives of stakeholder groups closely related to forest ecosystems, such as forest managers and businesses, which directly or indirectly market forest products (timber and non-timber products). Excluded were the local population, tourists and policy-makers. The focus was on local stakeholders who were from the region covered by the study area, as well as regional representatives of national or international organisations and scientists. The selection of potential participants was partly based on personal contacts and partly on a systematic approach. Not all invited groups were represented in the workshop and questionnaires due to lack of relevance of the research topic or time. To secure a larger, more representative group, stakeholders from outside Brandenburg were asked to participate. Nevertheless, some gaps still remained.

2.3 Methods applied in the dialogues

Methods used in stakeholder dialogues need to be tailored so that they fit the objectives. Two kinds of tools for stakeholder dialogues can be distinguished: tools for facilitating communication (communication tools) and tools for formalising actors' mental models, assessments, etc. (analytical tools) (Welp and Stoll-Kleemann 2006). Analytical tools can be applied to complement and support communication tools. Approaches such as Bayesian Belief Networks can be used to formalise stakeholders' assessments (Welp et al. 2006). Structuring and framing the research problem at hand can benefit from conducting group model building exercises (Vennix 1999) or by eliciting mental models of stakeholders (Morgan et al. 2002), or by combining both methods.

Workshops, brainstorming sessions, and regular teleconferences have been used by ECF in a search for new socially relevant and intellectually challenging research questions. Various controversial themes, such as the potential of biofuels in the transport sector, have been discussed in some technical and economic detail and documented in proceedings. A way to approach the broad public and experts in the academic, NGO and business world has been to draft discussion papers. Such papers, for example on long-term climate policies, have been published in refereed journals while press releases targeted the general public (Hasselmann et al. 2003). The writing of such discussion papers in small writing teams has provided an opportunity for mutual learning. For example, the ECF discussion paper "The Challenge of Long-Term Climate Change" was drafted by a group which was formed at the annual ECF conference 2002. This paper did however not represent an ECF consensus view, since the forum does not endorse specific views expressed by its members.

ECF has promoted and been closely involved in the development of communication tools, most notably of climate computer and board games. A computer game for two players was launched in November 2002 at a climate exhibition in the 'Deutsches Museum', Munich. In the game, players control future climate policy by adopting the role of either the government, a Chief Executive Officer of a global company or a typical private household from an industrialised country. The players endeavour to maintain a sustainable climate in the future while pursuing their own individual welfare goals. According to a survey among visitors to the Museum, the game was evaluated as being interesting and fun to play. Usually visitors played the game for 15 minutes.

Finally the internet has also been one important communication tool: documents, software and a climate game have been made available to interested people around the world. Email circulars have been effective in informing members of new events, publications or opportunities for cooperation. The public outreach activities of ECF have included besides discussion papers (Hasselmann et al. 2003) also press releases.

A board game (Winds of Change) was developed in close collaboration with the Munich Reinsurance Company. This game depicts challenges in technological learning, investments and keeping climate warming beyond dangerous levels and has been applied with stakeholders from the business world as well as students. ECF also supported the development of a further board game (Keep Cool), where players play a decision-maker of a region (such as Europe, USA, developing countries, etc.). The ECF family of climate games[7] thus comprises at the moment one computer game and two board games, which can be used in fostering team learning on climate change.

Within ATEAM, networking and contacting stakeholders has been a major activity throughout the project. Communication and dissemination material included flyers that have been produced in different languages, posters, executive summaries and full reports of meetings, a webpage[8] and facilitation/moderation during events. Activities included stakeholder workshops, questionnaires and interviews. The main dialogue focus of ATEAM has been in presenting its research, obtaining feedback from stakeholders, and seeking ways of accommodating stakeholders' suggestions within the pre-defined ATEAM framework. The specific objectives of each event were shaped to evaluate the progress of the research either in plenary or in dedicated sectoral working groups. Additionally stakeholder questionnaires and interviews of ATEAM scientists were carried out as part of the evaluation of the dialogue's outcome. Finally, independent observers participated in each general stakeholder meeting and provided the stakeholder dialogue coordination team with critical feedback, which helps to improve the following events.

Half way into the project it became clear that a digital compilation of the project's most salient results would be a useful communication tool for interested stakeholders. This led to the development of the ATEAM Atlas of European Vulnerability[9] (Metzger et al. 2004 and http://www.pik-potsdam.de/ateam/). The tool allows users to select indicators of impact and vulnerability, using the socio-economic, climate and land use scenarios they are most interested in. The maps are placed in a fact sheet, which provides succinct information on the models and scenarios used, the main assumptions made, the indicators themselves and additional references. Whenever aggregated or relative indicators are shown, users can decompose the results into their components or choose to view absolute data. Furthermore, users can perform simple queries, as well as focus in on specific environmental regions or countries. During final dialogue activities, stakeholders viewed early versions of the tool and commented on ways to improve it.

The SilviStrat project used a combination of communication and analytical tools. A workshop was organised in cooperation between PIK and the Landesforstanstalt Eberswalde (Brandenburg) to identify forest management objectives and the preferences of 23 stakeholders. The workshop started with a brainstorming session in which important forest functions were identified. Later on the group elaborated these main functions. The relevance of different forest management objectives was evaluated with the help of a questionnaire, which each stakeholder was asked to fill in. A summary of the presentations, discussion and findings of the workshop was sent to all interested parties. Stakeholders who could not participate in the event were also asked to fill in the questionnaire.

Forest management objectives and preferences of stakeholders were investigated using

[7]Further information about the ECF family of climate games can be found on the web site: www.european-climate-forum.net/games

[8]Some of this material is available at: //www.pik-potsdam.de/ateam/stakeholderweb/ateam_ stakeholder_material.html

[9]The ATEAM Atlas of European Vulnerability is available to download at: www.pik-potsdam.de/ateam/

Saaty's Analytical Hierarchy Process (AHP) and Saaty's eigenvalue method (Saaty 1990). The AHP is a mathematical method for analysing multi-criteria problems. The forest management objectives are ranked by pair-wise comparisons where stakeholders have the option to express their preference between two functions on a rating scale from equally important to absolute priority. The ratings are arranged in a symmetric matrix and the local priorities of the elements in the matrix are calculated by the normalised right eigenvector. The expected utility of alternative management options was calculated by means of a multi-criteria analysis method based on an additive utility theory (Kangas and Kangas 2002; Lexer 2000), which incorporated results from the stakeholder dialogue. The potential success of simulated forest management plans were analysed and trade-off effects between conflicting objectives were discussed.

The three examples thus applied very different tools ranging from games to computer models. The originality of SilviStrat's and ATEAM's stakeholder dialogue exercises was that the results derived from the dialogue were directly used in model development. SilviStrat used multi-criteria analysis to reflect with stakeholders on management alternatives in the forest sector. ATEAM developed innovative land use scenarios and an interactive interface for integration of its main results: the ATEAM mapping tool and Vulnerability Atlas (Metzger et al. 2004). ECF created different communication tools including board and computer climate games. All projects developed diverse and lively stakeholder networks and created situations in which stakeholders were confronted with state-of-the-art science on climate change.

2.4 Reflections

2.4.1 How can we evaluate science-based stakeholder dialogues?

What are adequate and useful evaluation criteria for science-based stakeholder dialogues? Oels (2006) gave an overview of some approaches to evaluation. In the following we will expand on this and focus on criteria that are especially relevant for science-based dialogues. Criteria that can be used for other participatory processes, such as city or road planning, do not necessarily apply to scientific dialogues. The main reason for this is that in planning and decision-making a consensus or clear majority view regarding a decision or action is striven for. In scientific dialogues on the other hand, a consensus view may emerge, but it is not the primary aim. Disagreement may prevail, as it often does, and shape future research. Nevertheless, evaluating stakeholder processes faces similar difficulties as when evaluating other participatory processes.

Evaluation of science-based stakeholder dialogues helps to adjust the course of the exercise and improve it gradually. There are few papers exploring the theoretical underpinning and practical steps of evaluating science-based stakeholder dialogues. However, relevant literature can be found in adjacent areas of evaluation, such as critical theory (Webler 1995), risk communication (Rowe and Frewer 2000), public participation (e.g. Webler 1995, Rowe and Frewer 2000) and democratic theory (Fiorino 1990). A distinction can be made between evaluations conducted by outsiders and participatory evaluations. While outsider evaluations are said to be independent and less biased it is important to have, in addition, evaluations from the participants themselves. The latter is viewed as credible and useful because the diverse needs of participants are more likely to be fulfilled (Chess 2000).

Important criteria to evaluate stakeholder dialogues are accountability, performance and direction (Abrams et al. 2003). Accountability means that scientists are accountable to the invited stakeholders and focus on transparency (free flow and access to all relevant information). Performance includes responsiveness to stakeholder concerns, effectiveness and efficiency (making the best use of resources) as well as using adaptive approaches. Direction finally focuses on strategic vision and effective leadership (how new ideas are generated and innovative processes to address and resolve difficult issues launched) as well as the use of collaborative learning in various forums.

A main distinction can be made on the object of the evaluation. This can explore how stakeholder dialogues take place (process evaluation) or assess the results themselves (outcome evaluation). Both can be performed during and/or after stakeholder dialogue efforts. It is useful anyway to reach consensus between the participants in advance on which goals to evaluate. For science-based stakeholder dialogues outcome-related evaluation is likely to be the most relevant one (e.g. was a stakeholder dialogue beneficial in identifying faults and gaps in the research strategy?). The output of the stakeholder dialogue should have a genuine impact on the research carried out (criterion of influence). One danger of science-based stakeholder dialogues is that some projects often only want to fulfil the conditions of research funding agencies, which increasingly require stakeholder dialogues as components of research projects without there being any intent of considering the knowledge of stakeholders formulated in the science-based dialogue. One approach that might lead to fulfilling this criterion is to ensure that there is a clear acceptance from all participants beforehand as to how the output will be used and how it might direct research. A more process related criterion is that of transparency. It means that the stakeholder dialogue should be transparent so that the stakeholders can see what is going on and how they influence the research process. The nature and scope of the stakeholder dialogues should thus be clearly defined. It is important to ensure that there is reflection regarding the scope of a stakeholder dialogue and its expected output. The effectiveness of a procedure, as well as its credibility, is likely to be influenced by any dispute caused through misunderstandings. Documenting the process of reaching a shared view (as well as the outcome) will increase transparency, and hence the credibility of the exercise. Furthermore it will increase the efficiency of the process.

2.4.2 Achievements

ECF has consolidated a rich and dynamic network of stakeholders. The main difference to other networks, such as the MIT Energy Modelling Forum, PEW Foundation, Climate Strategies (RIIA) and the Electric Power Research Institute (EPPRI), is the focus on joint studies and exchange of arguments among members with very different interests. In contrast to the ATEAM and Silvistrat projects which lasted only some years, the ECF was created as a permanent structure. ECF has for example positively contributed to structuring the debate on “What is dangerous climate change?” As a result of an international symposium in Beijing scientists and stakeholders came to the conclusion that a 2°Celsius increase in global mean temperature over a long period of time would be dangerous for ecosystems and humans (ECF (European Climate Forum) 2004). This message was conveyed and well received at a side event of the United Nations Framework Convention 10th Conference of Parties in Buenos Aires, Argentina. The development of climate games has been an activity that has given ECF public visibility. Games can be used as communication tools to engage people in thinking about and discussing climate change in an entertaining way. Coupled climate-economy models have served as a point of reference for game development, in particular in the development of the computer game.

ATEAM’s achievements through stakeholder involvement are significant. Firstly, a group of leading natural science modellers opened up to stakeholder interactions and more generally to the need of integrating social sciences in ecosystem modelling. The stakeholder participation has in itself been a powerful driver for more interdisciplinarity and a continuous help to focus and prioritise research efforts and resources to better address stakeholders' needs. Secondly, scientists were instead led to question the basic assumptions, methodologies and indicators used in their scenarios and models, the meaningfulness of the models themselves and of their results (incl. specific temporal and geographical scales) for stakeholders. Thirdly, efforts were mobilised to address stakeholders' suggestions when time and resources allowed this. For example additional case studies were carried out, the focus of one PhD thesis was significantly changed and specific modelling indicators were adapted to better suit issues raised by stakeholders. When stakeholders' recommendations could not be catered for within the scope and time-horizon of the project, they contributed to drawing a future research agenda, which fed ongoing research. That the ATEAM modelling and assessment approaches achieve clear scientific credibility was critical for stakeholders, who also placed a high value on the transparency of the methods used for aggregation and integration of the results. This has influenced vastly the ATEAM research work plan. Indeed this led to the development of innovative analytical and communication tools to promote better understanding of potential global change impacts on ecosystem service provision. In particular, the integrated vulnerability mapping methodology and mapping tool, as well as the concept of summary map information sheets were designed to address this very need. Consequently, scientists participating in the process have gained a more open attitude to participatory research since they have had direct, positive experience that this can be stimulating and fruitful, despite being resource and time consuming (see de la Vega-Leinert et al., in review for a more detailed evaluation of the ATEAM stakeholder dialogue).

In the SilviStrat project stakeholders played a key role in the research process. The results of the stakeholder dialogue were essential in particular for the regional study within SilviStrat. The multi-criteria analysis method that was applied in the study of forest management needed the inputs of stakeholders. These rankings were in past research projects provided by scientists/experts rather than by professionals in the forest sector. Stakeholders' assessments have now been integrated into the process and therefore the study is more closely linked to local knowledge on the management level. The dialogue helped to understand stakeholders' concerns, problems, restrictions and uncertainties in current forest management and under the aspect of changing climate. The project results provided an overview of differences and similarities of stakeholder interests in relation to forest ecosystem management. Stakeholders identified new research questions during the research process. These were collected and either addressed in the ongoing SilviStrat project, or if this was not feasible, used in drafts of future research projects.

By and large PIK has established itself as an institute which is interested in, and has gained the capacity to conduct stakeholder dialogues, which are of interest for both scientists and people outside the scientific community. It is also important to note that PIK is performing this together with other European and international research institutes. Since the time stakeholders can dedicate to such activities is limited, a coordinated effort among researchers and research institutes creates synergies and increases the efficiency of such dialogues.

2.4.3 Dealing with different expectations

Stakeholders may have different views on what the objectives and outcomes of a dialogue may be. It is important to reflect on the expectations and to develop a shared view on what stakeholders and scientists may gain by engaging in the time-consuming effort of stakeholder dialogues. Reflecting on these expectations should be part of the evaluation scheme of scientific stakeholder dialogues.

Within ECF the agenda is set jointly by scientists and stakeholders. Joint studies can be created flexibly if the provided resources are available. In other types of research projects the possibility to change research strategies is more limited since they are funded projects, which have an agreed research programme and products to deliver to the funding agencies. Thus for example ATEAM and SilviStrat have made successful and useful incursions into participatory integrated assessments. Although the full diversity of stakeholders' needs and preferences could not be catered for, flexibility and adaptation has been developed to explore new research directions when stakeholders' suggestions suited the interests, expertise and willingness of the involved scientists.

Although stakeholders' and scientists' interests sometimes differ, strong efforts have been made to listen carefully to, and accommodate the expectations and research needs of stakeholders. Within ECF new research areas have been intensively searched for and debated. Research projects were mostly easily agreed upon and initiated (e.g. project on the role of telecommunication in CO_2 reduction). However in one instance a proposed project on carbon capturing and sequestration (CSS) was subject to heavy debate. Some stakeholders considered carbon sequestration as an unacceptable technical fix, and were strictly against such a project and considered the issues as a no-go area. Others saw it as a potentially low cost technology for climate mitigation. Embedded in a broader assessment of technological options, carbon capturing and storage were eventually accepted for a project proposal. The framing of the research question is thus of great importance: many climate-related issues can be framed either as narrow technological questions which put aside for example the question of societal acceptability, or as a broader set of social-scientific and natural-scientific sub-questions.

Researchers are not always ready to engage in dialogues with stakeholders. Dialogues in natural sciences are a very recent development and many natural scientists have hardly dealt with dialogue methods (which have more affinities to social sciences). At the beginning of the ATEAM project, some scientists in the consortium were uneasy about the decision to engage in dialogue activities. The project had chosen to step out of the known paths of fundamental ecological modelling research and there was some uncertainty on whether this was a valid choice from the scientific point of view, and on how to perform this well. In the peer community some viewed this initiative 'at best' as a marketing trick to attract funding or 'at worst' as a 'non scientific' goal, which would discredit the project's overall scientific credibility. The project leadership thus took a significant risk and had to dedicate much time to convincing some project members and peers that it would be worth the effort. The latter was achieved by not compromising in core parts of the research plan (e.g. the detailed modelling developments and the benchmarking exercise, see Morales et al. 2005), which were not presented to stakeholders. These formed the main scientific achievements per se of the project, and guaranteed scientific credibility in the ecological modelling peer community. As consensus was forged on the originality and feasibility of the overall methodology, including the generic adaptive capacity index, and of the importance of the stakeholder dialogue component, the project achieved scientific recognition also in the interdisciplinary global change assessment community. Explicitly, the dialogue has aimed at elucidating ATEAM's work to raise stakeholder interest on the future results, and awareness on potential impact of global change. Implicitly however ATEAM scientists aimed at obtaining an overall consensus on the validity of ATEAM's approach through plenty of room for discussion on the limits of the research and needed future improvements.

Within SilviStrat the aim was a wide-spread understanding of forest services and functions which are required by various groups. One particular problem was to secure the participation of stakeholders from the wood industry, tourism and water management. Due to lack of time or the low priority they gave the workshop these groups were not represented. Furthermore representatives of environmental organisations had a forest-related background and therefore did not present a strict nature conservation point of view. Thus the dialogue between stakeholders was not as controversial as expected.

2.5 Conclusions: dialogue practice in view of the Integrative Theory of Reflexive Dialogues

The selection of stakeholders contacted for a dialogue exercise is, consciously or not, biased towards some specific actors rather than others. As discussed by Welp and Stoll-Kleemann (2006) and Stoll-Kleemann and Welp (2006), stakeholder dialogues are distinct from public participation exercises in that they do not aim at achieving a representative sample of the population, but rather a wide range of different opinions on a specific topic. Before initiating a dialogue exercise the spectrum of interested parties should thus be identified, leaving aside those which do not seem relevant to the problem at hand. In this selection process the personal networks, preferences, interests and priorities of the researcher will induce some amount of bias towards specific actors. To minimise this, a systematic selection process can be developed to complement the often used 'snowball approach' (Biernacki and Waldorf 1981). The creation of a stakeholder database can play a critical role not only in storing and analysing contact information of individual/organisations approached, but also their background, expertise, level of interest for the research topic, as well as any further contacts they might have suggested. However, if biases may be restricted at the selection and invitation phases, others will appear as stakeholders accept or decline invitations. Stakeholders are often busy and need to be convinced that they will gain significant benefits before they commit time and effort to activities which are not the focus of their work. Communication skills and a strong feel for how to engage stakeholders and demonstrate the relevance of the dialogue process for their personal activities will certainly help in gaining stakeholder support. Nevertheless in some cases the research/dialogue topic is simply too disconnected from stakeholders' activities to secure their interest and participation. Since biases cannot be avoided, reflecting on these and on their influences on the dialogue process and outcomes is an important step in evaluating the dialogue's achievement as well as in planning future exercises.

Citizens, i.e. non-expert lay persons, were not in the focus of any of the above-mentioned case studies. This was however the targeted audience of an earlier project carried partly out at PIK. The ULYSSES project engaged 600 citizens in structured Integrated Assessment Focus Group sessions to discuss climate change impacts and possible solutions (Stoll-Kleemann et al. 2001; Kasemir et al. 2003). Participants were confronted with the latest knowledge on climate change and synthesised their newly gained understanding in citizen assessments of the causes and impacts of climate change. These included suggestions on mitigation and adaptation measures (e.g. within the transport, energy and household sectors) as well on who should act, where and when. Welp et al. (2007)) have pointed out that such exercises should be linked to parliamentary decision-making more strongly than has been the case so far.

The integrative theory of reflexive dialogue as outlined by Welp and Stoll-Kleemann (2006) highlights the need to incorporate both analytical and communication tools in stakeholder dialogues. In all three case studies both types of tools were used. The examples can be characterised as dialogues with a focus on expert stakeholders. Although ECF engaged also in dialogues with lay person and studied for example their perception of the movie "The day after tomorrow" (Reusswig et al. 2004), the vast majority of contacts were climate change experts, such as representatives of companies, NGOs, and government bodies.

Social psychological theories are highly relevant for science based stakeholder dialogues, since group processes, and prejudices often play an important role especially in the phase where relationships between researchers and stakeholders are consolidated (trust building). This usually takes some time and being aware of such process may help to design meetings and events in a manner where personal relationships can evolve. Linked to the aspect of trust is that that expectations of those involved in science-based stakeholder dialogues need to match reasonably well. It is important to be explicit about them and to make the rules of the game clear at an early phase of the dialogues. During the course of dialogues the expectations may change and it is important to be flexible in this respect too. Thus being explicit about the objectives is key requirement for a working relationship based on trust.

Theories of organisations learning are helpful in finding out how representatives of different organisations can jointly create shared meaning. The development of a language which is understandable for all participants is a key element of science-based stakeholder dialogues. In discussions and dialogues language is created and altered. Communication and analytical tools thus complement each other. Analytical tools help in structuring an issue and in finding the crucial differences between the assessments of different individuals.

Science-based stakeholder dialogues are structured communication exercises, which are directed by researchers. Although stakeholders' views are taken into account, the choices on the ultimate research direction remain the responsibility of the scientists. In some cases decisions are made jointly by scientists and stakeholders. Critics of the current practice of scientific-based stakeholder dialogues often claim that for scientists dialogues appear to be a substitute for 'real scientific inquiry'. They argue that stakeholders are consulted and asked to provide the important parameters, conceptualise problems and do the actual thinking. This view is based on a misconception of what scientific dialogues aim at. Good research increasingly takes place in small interdisciplinary teams, in which the individual scientists meet regularly to think together. Science-based stakeholder dialogues are an extension of this practice and an effort to bring together even more different knowledge domains than the different academic disciplines. Stakeholder dialogues are not a substitute for thinking but rather they foster the art and practice of thinking together.

Chapter 3

Analysis of adaptive forest management practices under climate change

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Abstract

In European forests timber production and carbon sequestration may vary with management strategies. To mitigate possible negative effects of a changing climate and to enhance carbon sequestration adaptive management practices were studied within the scope of the EU project SilviStrat. In this study we present a model-based evaluation of the economic consequences of such adaptive management practices at a Scots pine and a Norway spruce stand in Germany, using the forest growth model 4C (FORESt Ecosystems in a changing Environment).

For this purpose, a set of stand treatment programmes (STP) with varying thinning intensity and rotation length for each site was carried out under current climate and two climate change scenarios for 100 years. The model delivered information on carbon in the forest (stand and soil), carbon in harvested and extracted forest biomass, marketable timber by timber grades and species and their allocation to the production lines of a wood product model.

Results of the simulation experiments were analysed with respect to the forest functions: timber production, carbon sequestration in the forest and in wood products, biodiversity and groundwater recharge using the management preferences of three different forest user groups. Applying a multi-criteria approach conflicting management objectives were pointed out. Potential marginal costs of carbon sequestration of about 32 € t C^{-1} for the pine stand and 24 € t C^{-1} for the spruce stand illustrate the trade-off between maximising timber production/income versus maximising carbon sequestration.

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3.1 Introduction

The study aims at the analysis of potentials of forest management to increase carbon sequestration in forest and wood products and to mitigate possible negative effects of climate change. The analysis focus on management options on stand level. The work was a part of the EU project SilviStrat ("**Silvi**cultural Response **Strat**egies to Climatic Change in Management of European Forests") which addressed the impacts of climate change on forests and the analysis of management strategies to adapt to climate change and to mitigate adverse impacts, which climate change may have on forests and forestry.

The analysis of management strategies includes an economic evaluation and an estimation of marginal costs of carbon sequestration to investigate the trade-off in forestry between timber production and carbon sequestration. Furthermore, the effects of climate change on these costs are analysed.

3.2 Material and methods

3.2.1 Overall approach

The presented study was focussed on a model-based analysis of a variety of management treatments programs (STP) at two sites for two species under current climate and two scenarios of climate change. The forest dynamics model 4C ('FORESEE' - **FORES**t Ecosystems in a changing **E**nvironment) was applied and a defined set of output variables was generated for the evaluation of STPs. The output variables were analysed with the Wood Product Model WPM (Eggers 2002) to calculate carbon resilience times within wood products, landfills. For the valuation of the economic performance of the simulated STPs the net present value (NPV) and other economic parameters were calculated. Finally, a multi-criteria analysis of the stand treatment programs was done using an existing approach which was successfully applied for silvicultural decision making (Lexer 2000; Vacik and Lexer 2001).

3.2.2 Model 4C

The model 4C was developed to investigate long-term forest behaviour under changing environmental conditions (Bugmann et al. 1997; Schaber et al. 1999; Lasch et al. 2002). It describes forest processes at tree and stand levels on the basis of findings from eco-physiological experiments (e.g. Medlyn and Jarvis 1999), investigations of tree growth and architecture (e.g. Burger 1948), and long-term observations of stand development, and physiological modelling (e.g. Haxeltine and Prentice 1996). The model simulates tree species composition, forest structure, and leaf area index, as well as ecosystem carbon and water balances. It shares a number of features with older forest-gap models (Botkin et al. 1972; Bugmann 2001) which have often been used for the simulation of long-term forest development. Establishment, growth, and mortality of tree cohorts are explicitly modelled on individual patches, on which horizontal homogeneity is assumed.

Currently the model is parameterised for the five most abundant tree species of Central Europe (beech, *Fagus sylvatica* L.; Norway spruce, *Picea abies* L. Karst., Scots pine, *Pinus sylvestris* L., oaks, *Quercus robur* L., and *Quercus petraea* Liebl., and birch, *Betula pendula* Roth). The 4C model requires weather data (temperature, precipitation, air vapour pressure, solar radiation, and wind speed) with a daily resolution. The model allows the simulation of management of mono- and mixed species forests. For this purpose, a variety of thinning, harvesting and regeneration strategies are implemented. A grading module delivers timber grades according to a German timber classification system (HKS) of the harvested timber and the standing stock.

3.2.3 MCA and utility model

The forest management strategies were evaluated with regard to multiple management objectives using a multi-criteria analysis (MCA) method. This method provides the possibility to analyse the conflicts between management objectives and to integrate a participatory approach. For analyses in SilviStrat and this study a combination of the Analytical Hierarchy Process (AHP) and a multiple attribute theory (MAUT) was used (Saaty 1977). This approach allows estimating an overall stand utility of a STP based on an additive utility function U, which was defined in the following way:

$$U = \sum_{i=1}^{4} a_i \cdot U_i \qquad \text{with the constrain:} \sum_{i=1}^{4} a_i = 1 \tag{3.1}$$

The functions U_i are the partial utility functions of the management objectives timber production (i=1), carbon sequestration (i=2), biodiversity (i=3) and groundwater recharge (i=4), which were selected for this study. The partial objective timber production is composed of preferences regarding NPV (net present value, j=1), MAI (mean annual timber increment, j=2) and SV (mean standing volume, j=3):

$$U_1 = \sum_{j=1}^{3} a_j \cdot P_j \qquad \text{with the constrain:} \sum_{j=1}^{3} a_j = 1 \tag{3.2}$$

The parameters in equation (3.1) and (3.2) were estimated by the eigenvalue method in the AHP. This method is based on pair-wise comparisons of the elements in the decision hierarchy (Figure 3.1) which was chosen for this study.

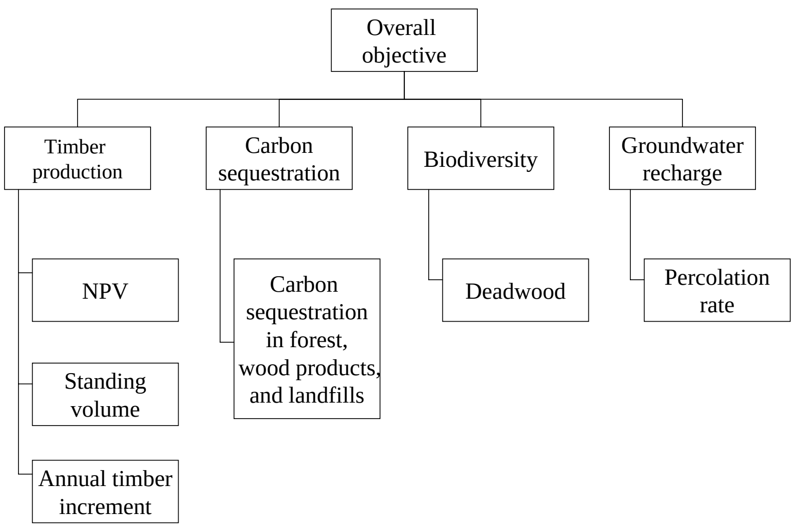

Figure 3.1: Decision hierarchy at stand level. NPV = net present value (interest rate p = 0.02).

At a stakeholder workshop representatives of forest user groups identified these management objectives and analysed the decision hierarchy by a questionnaire. The results of three forest stakeholders, forest manager (FM), private forest owner (FO) and representative of an environmental organisation (EO), were used for this study (Table 3.1).

Table 3.1: Priorities of management objectives and criteria.[1]

Objective	Priority			Criteria	Priority
	FM	FO	EO		
Timber production	0.61	0.67	0.25	NPV	0.43
				MAI	0.43
				Standing volume	0.14
Carbon sequestration	0.05	0.11	0.25	Total carbon	1.00
Biodiversity	0.17	0.18	0.25	TDead wood	1.00
Groundwater recharge	0.17	0.04	0.25	Percolation	1.00

[1] Some numbers of the table were by mistake wrong in the original version of the paper and are corrected in this version

The preference functions U_i and P_j were defined using expert knowledge for both species. Figure 3.2a-c shows the functions developed to characterise the decision variables of timber production for the species Norway spruce.

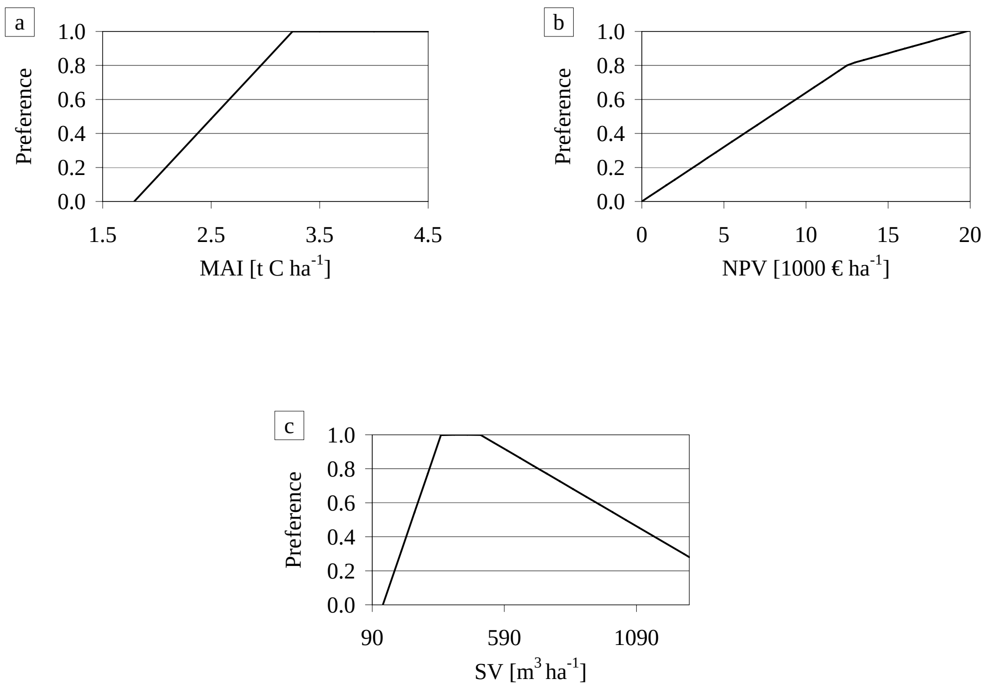

Figure 3.2: Preference functions for spruce (MAI = mean timber increment, NPV = net present value, SV = standing volume).

3.2.4 Sites and scenarios

The analysis of STPs is presented here for two German sites, a Scots pine stand in Brandenburg (site Chorin) and a Norway spruce stand in Saxony (site Grillenburg). At both sites data from long-term management trails are available for model initialisation. We selected data for initialisation of a juvenile, pole and mature stand to describe typical age classes of forest stands. For each stand initialisation STPs were generated combining the usual rotation length (120 years) and a shorter and longer rotation length with the usual moderate thinning intensity which was alternatively varied to heavy and slight thinning intensity (Table 3.2).

Table 3.2: Site and management characteristics.

Site	Age of stand	Rotation length	Thinning intensity	Thinning/harvesting
Chorin	17/48/100	80/120/160	heavy/ moderate/ slight	Thinnning from below and clear cut
Grillenburg	31/68/100			

This program results in 9 STPs for each stand initialisation and an additional STP called 'no management'. The STPs were numbered as shown in Table 3.3.

Table 3.3: Definition of the STPs by rotation length (RL) and thinning intensity (TI)

	1	2	3	4	5	6	7	8	9	10
RL	80	80	80	120	120	120	160	160	160	-
TI	heavy	mod.	slight	heavy	mod.	slight	heavy	mod.	slight	-

The model simulated 100 years under current climate and two climate change scenarios delivered by the project SilviStrat. The current climate time series was based on Climatic Research Unit (CRU) monthly time series, 1901-1995, and the CRU monthly climatology 1961-1990, with a spatial resolution of 0.5°x 0.5°(Hulme et al. 1995). The ECHAM climate scenario was based on GCM (Global Circulation Model) output from ECHAM4-OPYC3 (European Centre Hamburg, Germany) and on the IS92a emission scenario assuming a doubling of atmospheric CO_2 concentration in the 21st century. The HADLEY climate scenario was based on GCM output from HadCM2 (Hadley Centre, UK) and on the same IS92a 'business as usual' emission scenario (Mitchell et al. 1995). The model used for the climate change scenarios an increase in atmospheric CO_2 corresponding to the LTEEF study (Erhard et al. 2001). The evapotranspiration was calculated using the approach of Turc and Ivanov (Wendling and Müller 1984).

The site Chorin is always dryer and warmer than the site Grillenburg situated in the foreland of the Ore Mountains (Erzgebirge). The climate change scenarios were characterised by a temperature increase varying from 2.1 K to 3.1 K over the whole period of 1990 - 2090. The annual precipitation sum did not change or decreased under the ECHAM scenario (ECH) and increased under the HADLEY scenario (HAD) at both sites (Table 3.4).

Table 3.4: Climatic characteristics of the sites and applied scenarios (CC = current climate, ECH = ECHAM scenario, HAD = HADLEY scenario).

Site	Mean annual temperature [°C]			Mean annual precipitation sum [mm]		
	CC	ECH	HAD	CC	ECH	HAD
Chorin	8.5	11.3	10.6	519	519	546
Grillenburg	7.4	10.5	9.8	824	756	829

3.3 Results and discussion

3.3.1 Forest productivity and carbon sequestration and climate change

The average net increment of timber, calculated by averaging the sum of harvested and harvestable timber over 100 years, increased with increasing rotation length at both sites (Figure 3.3) and increased more or less with thinning intensity (from STP 1 to STP 3 or STP 6 to STP 9). In the case of 'no management' this increment was clearly below the increments of the other STPs. Climate change had an overall positive effect on timber increment. At the dryer site Chorin (pine) the increases under climate change were higher than at the moister and more productive site Grillenburg (spruce).

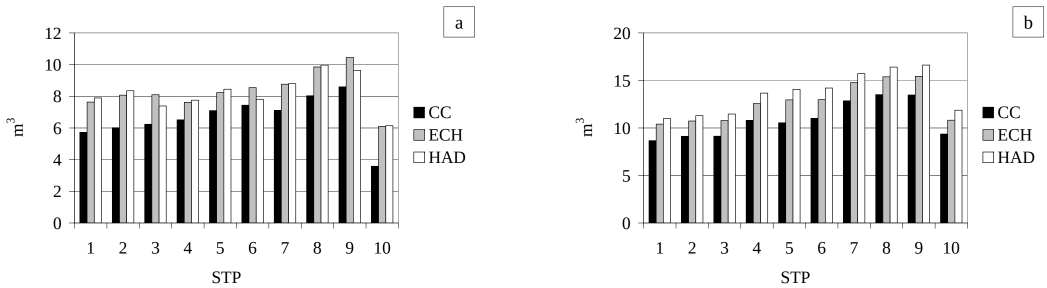

Figure 3.3: Average net increment of timber under current climate (CC) and climate change (ECH, HAD) of the pole pine stand (a) and the pole spruce stand (b).

For the evaluation of carbon sequestration a variable CS was calculated describing the net carbon gain over the whole simulation period in the forest (above- and belowground biomass, deadwood, and soil), calculated by 4C and in timber products and landfills, calculated by WPM. For pole pine and spruce stands CS was maximised by the 'no management' STP (Figure 3.4). Short and long rotation length generated higher CS than a medium rotation length for the pole pine stand whereas the CS of the pole spruce stand increased with rotation length. These results indicate positive effects of long rotation length under current and climate change. Conclusions should be carefully drawn because effects like higher risk of diseases in older stands were not considered in the model.

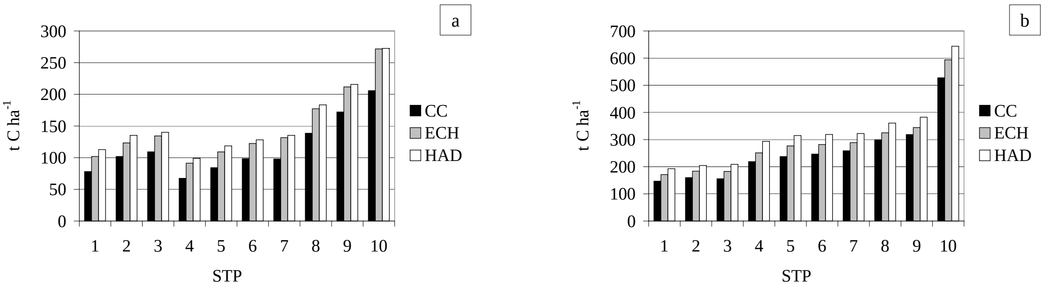

Figure 3.4: Carbon sequestration (in forest, wood products and landfills) under current climate (CC) and climate change (ECH, HAD) of the pole pine stand (a) and the pole spruce stand (b).

3.3.2 Multi criteria analysis

The overall stand utility (Figure 3.5a) was maximised by STP 9 (RL=160, slight thinning) for the pole pine stand from the viewpoint of the forest manager and forest owner. Both stakeholders have similar priorities (Table 3.1) regarding timber production. The representative of EO preferred the 'no management' STP. This was caused by a very high partial utility of biodiversity and carbon sequestration (Figure 3.5c) for this STP. It is necessary to note here that the partial utility of biodiversity, determined by the deadwood pool, is lacking of additional significant criteria for biodiversity.

Considering the spruce stand, STP 7 (RL=160, heavy thinning) realised a maximum stand utility caused by a maximum partial utility in timber production (Figure 3.5b and 3.5d). Again, the 'no management' program had a maximum partial utility for biodiversity and carbon sequestration and a minimum value for timber production which led to a maximum stand utility from the viewpoint of the EO. At both sites the groundwater recharge measured by the annual percolation rate did not affect the stand utility because the simulate percolation rates were relatively high due to the applied evapotranspiration approach.

The stand utility of the forest owner was maximised by the same STP (7) under the climate change scenarios as under current climate for the pole spruce stand (Figure 3.6). A maximum stand utility for the pole pine stand under the climate change scenarios was realised by STP 8 instead of STP 9 under current climate. This result indicated that the management treatments maximising stand utility under current climate realised also a good performance under both climate change scenarios resulting in an increasing productivity at both sites. The 'best' STPs regarding stand utility under current climate and climate change do not correspond to the usually applied STP, RL=120 with moderate thinning intensity, for pine and spruce stands. As discussed before foresters take into account the risks occurring in very old stands (i.e. damages caused by diseases or storm) or in stands with low density. Their decisions are based on knowledge and experience which is not completely modelled in the forest growth model 4C and in the decision hierarchy of the applied utility model.

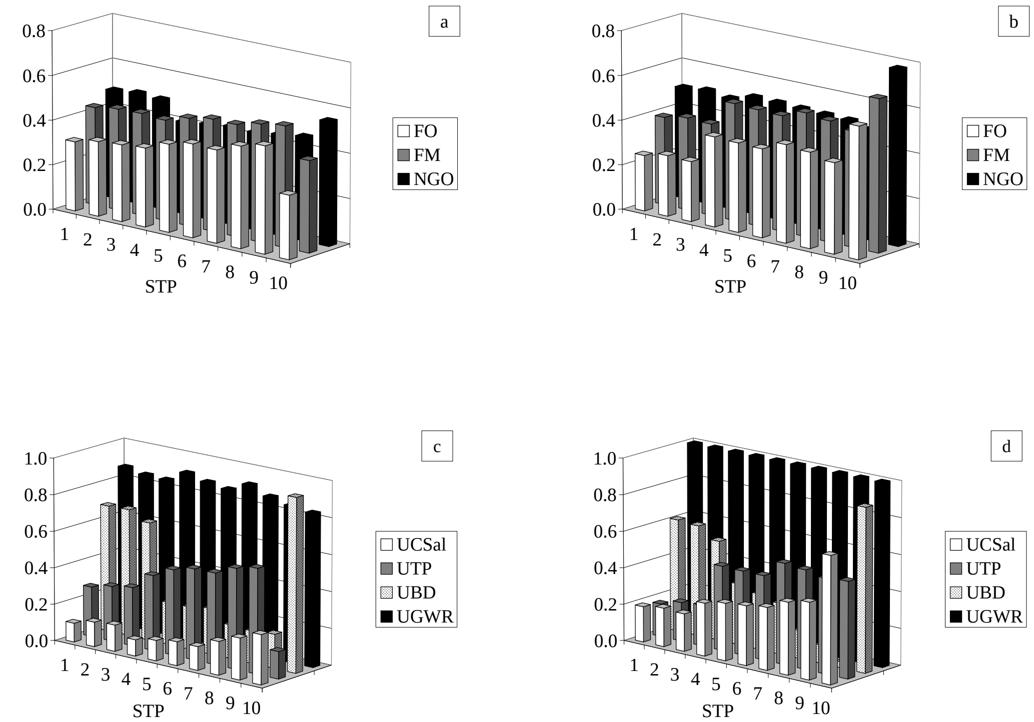

Figure 3.5: Overall stand utilities of the pole pine (a) and spruce (b) stand presented for three forest stakeholders (Table 3.1). The partial utilities of the pole pine (c) and spruce (d) stand presented for carbon sequestration (UCSal), timber production (UTP), biodiversity (BD), and groundwater recharge (UGWR).

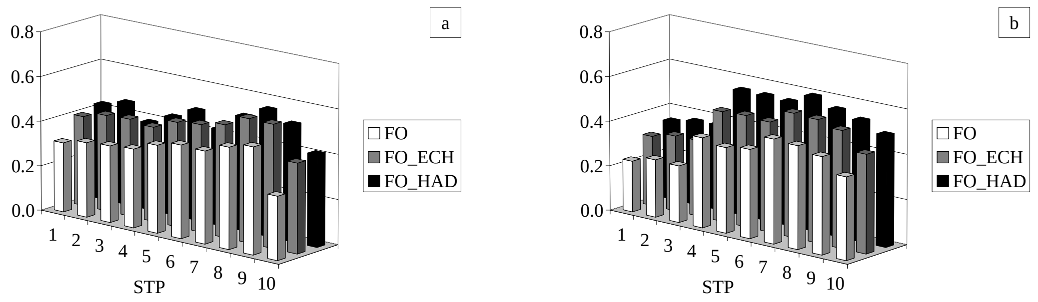

Figure 3.6: Overall stand utilities of the pole pine (a) and spruce stand (b) from the viewpoint of the forest owner under current climate (FO), ECHAM (FO_ECH) and HADLEY (FO_HAM) climate scenario.

3.3.3 Economic valuation

The conflict between management objectives is illustrated with the Spearman rank correlation analysis between net present value (NPV) and carbon sequestration. We analysed the rank correlation between the preference function values for carbon sequestration (CS) and NPV of the 9 STPs per age class and climate scenario. The Spearman rank correlation coefficients indicated a negative correlation varying from -0.17 to -0.85 for the pole and mature pine stand and a low positive correlation of about 0.37 for the juvenile stand between this two management objectives (Figure 3.7a). For all spruce stands the rank correlation coefficients were negative varying from -0.23 to -0.75. The climate scenarios did not change these correlations in principle. The mostly negative correlations pointed at loss in income if a management treatment was chosen which maximised carbon sequestration.

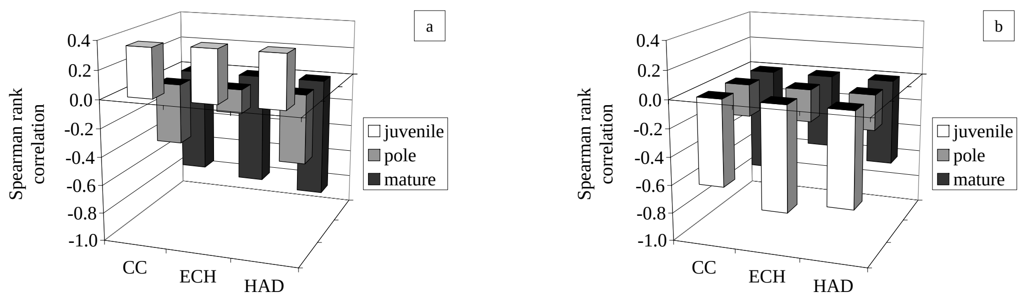

Figure 3.7: Spearman rank correlation coefficients for the pine (a) and spruce (b) stands between net present value and carbon sequestration under current climate (CC) and climate scenarios (ECH, HAD).

The cost of carbon sequestration in terms of Euro per tonne of carbon sequestered is a usual unit for cost-effectiveness calculations. In the project SilviStrat the flow summation approach was used (Newell and Stavins 2000): the discounted present value of costs (NPV) is divided by the totals of carbon sequestered (CS) regardless of when sequestration occurs. The potential costs of CS were derived from the differences in sequestered carbon and NPV of the best STP for carbon sequestration (STP 10 'no management') and income respectively.

The potential costs of carbon sequestration for the pine stand varied under current climate from 10 to 59 € tC^{-1} (32 € tC^{-1} on average) and decreased under climate change for the pole and mature stand (Figure 3.8a). This decrease is caused by the fact that on average of the three age classes the STP maximising income realised a higher CS over 100 years under climate change than under current climate (Figure 3.8b). The gain in carbon sequestration over 100 years clearly increased under climate change.

The potential costs of carbon sequestration for the spruce stand varied from 14 to 43 € per tonne of carbon sequestered (24 € t C^{-1} on average) under current climate (Figure 3.9a). Increased carbon sequestration under climate change over 100 years (Figure 3.9b) led to a slight decrease in potential costs. For both sites the costs were particularly high for mature stands because of the high losses in income if these stands are not harvested under the 'no management' strategy. The costs for the juvenile and pole stands were clearly lower and in the range of market prices discussed in the context of the Kyoto Protocol. The carbon sequestration differed between the sites and the climate scenarios and thus the losses in income on stand level if forest managers change the management from maximising income to maximising carbon sequestration.

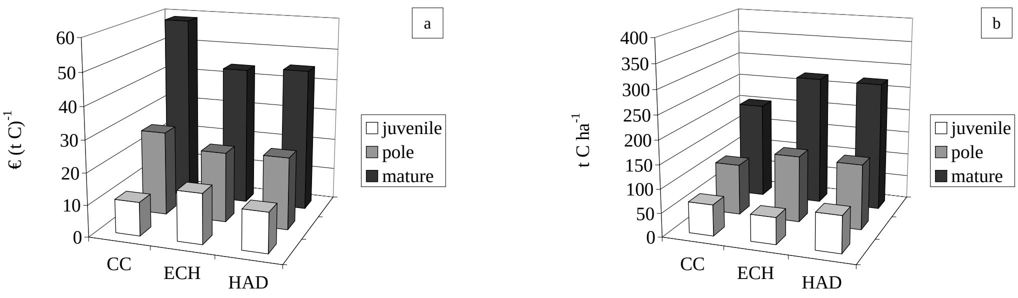

Figure 3.8: Potential marginal costs (MC) of carbon sequestration for the pine stand (a) and additional carbon sequestration over 100 years under these marginal costs (b).

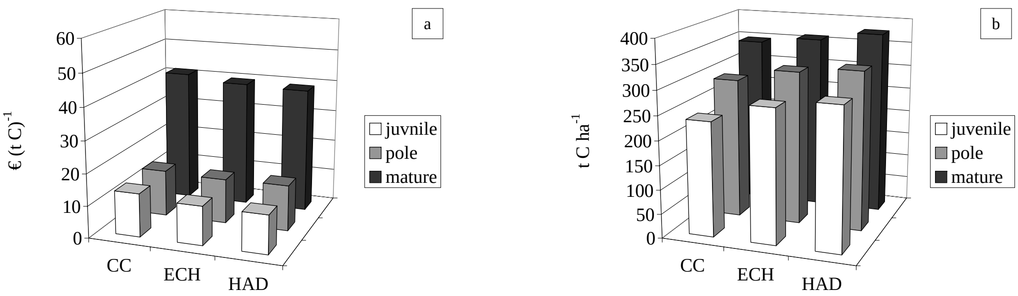

Figure 3.9: Potential marginal costs (MC) of carbon sequestration for the spruce stand (a), additional carbon sequestration over 100 years under these marginal costs (b).

3.4 Conclusions

This analysis serves as an example for the combined application of simulation tools for the evaluation of stand treatment programs under a variety of management objectives. The analysis at two sites under current climate and climate change demonstrates a suitable way to determine optimal management strategies with regard to a variety of management objectives incorporating different forest decision makers and stakeholders. For this application the optimal management strategies under current climate are more or less optimal under both climate scenarios which lead to increased carbon sequestration. The presented statements on optimal strategies are dependent on stand age because only three typical age classes were used. The analysis should be repeated based on a simulation experiment with a normal forest to get an evaluation independent on age. The economic evaluation underlines the trade-offs forest managers have to consider with regard to maximising their income and the demand for increased carbon sequestration.

Chapter 4

Multiple-use forest management in consideration of climate change and the interests of stakeholder groups

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Abstract

In this study, the overall utility of forest management alternatives at the forest management unit level is evaluated with regard to multi-purpose and multi-user settings by a multi-criteria analysis (MCA) method. The MCA is based on an additive utility model. The relative importance of partial objectives of forest management (carbon sequestration, ground water recharge, biodiversity, and timber production) is defined in cooperation with stakeholders. The forest growth model 4C (FORESt Ecosystems in a changing Environment) is used to simulate the impact of six forest management strategies and climate on forest functions. Two climate change scenarios represent uncertainties with regard to future climatic conditions. The study is based on actual forest conditions in the Kleinsee management unit in east Germany, which is dominated by Scots pine (*Pinus sylvestris* L.) and oak (*Quercus robur* L. and *Quercus petraea* Liebl.) stands. First, there is an analysis of the impact of climate and forest management on forest functions. Climate change increases carbon sequestration and income from timber production due to increased stand productivity. Secondly, the overall utility of the management strategies is compared under the priority settings of different stakeholder groups. From an ecological perspective, a conservation strategy would be preferable under all climate scenarios, but the business as usual management would also fit the expectations under the current climate due to high biodiversity and carbon

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sequestration in the forest ecosystem. In contrast, a forest manager in public-owned forests or a private forest owner would prefer a management strategy with an intermediate thinning intensity and a high share of pine stands to enhance income from timber production while maintaining the other forest functions.

Introduction

Climate change is expected to affect the altitudinal and longitudinal range of biomes, forest communities, and tree species (IPCC 2001) and influence the productivity of unmanaged and managed forests in response to changing environmental conditions such as higher winter temperatures, longer vegetation period, or increasing drought risk (Kramer and Mohren 2001). Hence, the relative suitability of species for the achievement of timber production goals will shift under climate change conditions. Climate change effects have also been described with respect to other goods and services provided by forests such as ground water recharge, support for biodiversity and maintenance of habitats, or landscape structure (Schröter et al. 2005; IPCC 2001; Lasch et al. 2002).

Objectives and constraints for decisions about future management not only arise from climate change. They are also affected by changing societal demands for multiple forest services that developed during recent decades (RSU (Rat von Sachverständigen für Umweltfragen) 2000). Such demands concern, for instance, ground water repletion, habitat for rare and endangered species, resources for game hunting, and a wide array of leisure activities. Recently, in a search for options for the mitigation of climate change, forests also have been proposed as potential additional sinks for CO_2 (Brown et al. 1996). Thus, forest management objectives are increasingly defined in the setting of a multi-purpose, multi-user scene. Hence, there is a need to establish and evaluate alternative forest management strategies (MS) taking into account uncertainty about future climates (Lindner 1999; Kellomäki et al. 2000) and the various sets of management objectives reflecting the demand for forest goods and services by different stakeholder groups (Lexer and Brooks 2005).

Some of the forests products, goods, and services are sold on markets and thus are comparable through projection into a common monetary denominator. However, many forest goods and services are consumed without being marketed commercially. Some, such as secure hiking trails, are by-products of the establishment of infrastructures for management operations and have to be provided free of charge in Germany on the basis of forest legislation and German Civil Code. Others, such as the air-filtering function, are achieved without a specific investment. To make management alternatives comparable within a multi-purpose setting, all forest goods and services have to be evaluated on a common scale of preferentiality. One option is cost-benefit analysis (CBA) that requires a breakdown into individual virtually-saleable products for which a monetary value has to be estimated by methods such as contingent valuation or hedonic pricing (Puttaswamaiah 2002). An alternative approach is provided by multi-criteria analysis (MCA). Such approaches require the definition of quantifiable decision criteria. The performance of alternatives with regard to these criteria has to be evaluated on a common relational scale of preferentiality (e.g. Kangas and Kangas 2005). Thus, both methods (CBA and MCA) are common in that they aim to quantify the appreciation of goods and services by their users. For the current study, we employ MCA-methodology for the comparative assessment of management alternatives. One management unit was chosen as study object to include a given set of initial forest conditions and ecological factors typical for the south-east of the federal state of Brandenburg.

The overall objective of the current study is to evaluate alternative MS at the forest management unit level under current climate and under transient climate change conditions over a planning period of 100 years. Specifically, the aim is to address the effects of different stakeholder priorities regarding management objectives on the preferentiality of alternatives and the related trade-offs among management objectives under different MS. Property rights and actual legal restrictions to forest use and management are disregarded in this analysis.

4.1 Methods and Material

4.1.1 Study area

The Kleinsee study area (14°31'E, 51°57'N) is situated in the south-east of the federal state of Brandenburg, Germany and comprises the public-owned forest of the Kleinsee management unit and the bordering southern part of the Pinnow management unit in the Peitz forest district. General characteristics of the forest stands in Kleinsee can be found in Table 4.1. The dominant soil types are Cambisols and subtypes with glacial sands as the main parent material and a mean groundwater table depth of 6 m. Soil fertility in Kleinsee (classified according to the East German scheme, depending on humus layer type and actual ground vegetation) ranges from poor to fertile with most stands on medium fertile sites. The climate is sub-continental to continental with an average annual precipitation of 563 mm and a mean annual temperature of 8.9°C.

Table 4.1: Detailed forest stand description of the study site Kleinsee.

Stand characteristics	Description
Size	952 ha
Natural forest ecosystem	Scots pine (*Pinus sylvestris* L.) dominated forest with Sessile oak (*Quercus petraea* (Matt.) Liebl.) and European white birch (*Betula pendula* Roth.) (Hesmer 1933)
Actual species distribution	62% Scots pine,
	30% oak species (*Quercus petraea, robur* and *rubra*),
	3.2% European larch (*Larix decidua* P. Mill.),
	Less then 2%: European white birch, Norway spruce (*Picea abies* (L.) Karst.), Douglas fir (*Pseudotsuga menziesii* (Mirbel) Franco), European beech (*Fagus sylvatica* L.) and Black locust(*Robinia pseudoacacia* L.)
Stand structure	Mostly even-aged stands
	Ca. 42 of the stands are stocked with more than one tree species, the usual mixture being pine and oak
Mean standing stock[1]	179 m^3 ha^{-1} (pine: 162 m^3 ha^{-1} and oak: 218 m^3 ha^{-1})

[1]Young stands are excludes from the calculation of mean standing stocks because their volume is not documented.

4.1.2 Models

The model 4C ('FORESEE' - **FORES**t **E**cosystems in a changing **E**nvironment) has been developed to investigate long-term forest behaviour under changing environmental conditions (Bugmann et al. 1997; Schaber et al. 1999; Lasch et al. 2002). It describes processes at the tree- and stand-level based on findings from eco-physiological experiments (e.g. Medlyn and Jarvis 1999), investigations of tree growth and architecture (e.g. Burger 1948), long-term observations of stand development, and physiological modelling (e.g. Haxeltine and Prentice 1996). The model simulates tree species composition, forest structure, leaf area index, as well as ecosystem carbon and water balances. Establishment, growth, and mortality of tree cohorts are explicitly modelled on individual patches for which horizontal homogeneity is assumed. An age- dependent growth reduction function was implemented as a new component. Currently the model is parameterised for five tree species of Central Europe (European beech (*Fagus sylvatica* L.), Norway spruce (*Picea abies* L. Karst.), Scots pine (*Pinus sylvestris* L.), oaks (*Quercus robur* L. and *Quercus petraea* Liebl.), and European white birch (*Betula pendula* Roth.)). 4C requires weather data at a daily resolution on variables such as temperature, precipitation, air vapour pressure, solar radiation, and wind speed.

The model 4C enables the simulation of management operations with different thinning, harvesting, and regeneration strategies (Lasch et al. 2005). The harvested timber and standing stock can be graded according to the German timber classification system (MELF (Ministerium für Ernährung, Landwirtschaft und Forsten) 1995). To reflect the harvesting situation in Kleinsee, the harvested timber is assorted into partial logs, industrial roundwood and fuelwood. Wood quality is not intrinsically modelled, but 40% of the volume of partial logs is classified as industrial roundwood to account for various timber defects (based on experience of forest service personal and literature (LFA (Forstliche Versuchs- und Forschungsanstalt Baden-Württemberg) 1993)).

Based on the timber grading and timber prices revenues can be calculated. Combined with harvesting costs and costs of silvicultural operations (Appendix B: Table B.4 and B.5) the net present value (NPV) of forest management can be calculated. Other costs, such as administration, maintenance, and road-building costs are neglected in this study. It is also assumed that costs and prices do not change throughout the simulation time. Carbon storage in the wood products pool is estimated with a wood product model WPM (Eggers 2002; Briceño-Elizondo and Lexer 2004). The WPM calculates the residence time of carbon in wood products and landfills. The harvested timber is distributed into different production lines depending on the type (hardwood or softwood) and the timber grade. Parameterisation is based on general figures for Brandenburg (BMVEL (Bundesministerium für Verbraucherschutz, Ernährung und Landwirtschaft) 2003a, 2004a) (Appendix B: Table B.6) and parameters from Eggers (2002). A life span function calculates the residence time of timber in products lines (Eggers 2002). Used wood products can be recycled, burned or placed in landfills. The WPM was initialised with the results of a simulation run characterising the possible development of carbon storage in the product chain over the last 50 years, based on the growth condition and tree species composition in Kleinsee.

4.1.3 Simulation runs

Information about forest stand and soil characteristics that were used for the initialisation of the simulations are listed in Table 4.2. Due to a limited number of parameterised tree species in 4C, deciduous trees other than those parameterised were handled as oak and coniferous tree species as pine. Only mono-species stands were simulated since the simulation of mixed stands in 4C has not been sufficiently validated thus far. Soil type and soil fertility class were allocated to each stand with either the local soil type or a general soil type being selected for the simulation runs, depending on the availability of detailed information.

The stands were classified into stand classes according to three criteria: (i) main tree species, (ii) age class (an age class comprises 20 years), and (iii) soil type and fertility. If a stand class did not contain an oak or pine stand, and therefore insufficient data for initialisation in 4C, or if the area of a class was smaller than 3 ha, then the class was combined with a similar stand class. This resulted in 43 stand classes.

4.1.4 Climate scenarios

The simulations were run over a 100-year period under a current climate scenario (CRU) and two transient climate change scenarios (Table 4.2) including concurrent changes in atmospheric CO_2. The mean values of temperature and precipitation of the last 20 years of the climate scenarios are compared to reflect the impact of the climate scenarios. The mean annual temperature of the last 20 years of the CRU scenario was 8.5°C and increased under the climate change scenarios to 11.9°C (HadCM2) and 13.1°C (ECHAM4) respectively. The mean annual precipitation sum of the last 20 years was 556 mm (CRU), 586 mm (HadCM2), and 528 mm (ECHAM4).

Table 4.2: Sources of the input data for the simulations with the forest growth model 4C.

Part of the program	Information	Source
Stand initialisation	Tree species, age, mean breast height diameter, mean height, standing volume, and basal area	Datenspeicher Wald 2000
Soil initialisation	Local soil type and soil fertility index	Site classification map of the management unit (Schulze 2000)
	General soil type	German digital soil map (BK 1000)[1]
Climate scenario CRU	Based on the Climatic Research Unit's (CRU) monthly time series 1901-1995 and the CRU monthly climatology 1961-1990, with a spatial resolution of 0.5°x 0.5°	
Climate change scenario ECHAM	Based on the GCM[2] output from ECHAM4-OPYC3 and IS92a emission scenario[3]	European Centre Hamburg, Germany
Climate change scenario HADLEY	Based on GCM output from HadCM2 and IS92a emission scenario	Hadley Centre, UK

[1]Bodenübersichtskarte der Bundesrepublik Deutschland 1: 1,000,000 generated by the Federal Institute for Geosciences and Natural Resources (BGR), Hannover

[2]GCM stands for global circulation model

[3]IS92a emission scenario assumes a doubling of atmospheric CO_2 concentration in the 21st century

4.1.5 Management strategies

In the current study, a total of six MS were analysed, including a conservation option that excludes any active management intervention. The MS were defined to reflect previous, actual and possible future MS. Each MS was further subdivided into operational stand treatment programmes. They vary in thinning regime, thinning interval, and thinning intensity, rotation period length, harvesting regime, and regeneration species (Table 4.3). Previous management mostly aimed at timber production. Therefore, the main tree species was pine managed in even-aged stands and harvested by clear-cutting. Today, the general principles of forest management defined in the Federal Forest Program of Brandenburg (MELF (Ministerium für Ernährung, Landwirtschaft und Forsten) 1993) and the silvicultural guidelines (MELF (Ministerium für Ernährung, Landwirtschaft und Forsten) 1998) aim at high stability and resilience of forest ecosystems and multi-functional forestry, facilitated by increasing the portion of deciduous tree species and the abandonment of clear-cuts.

Table 4.3: Description of the management strategies (MS). (Harvesting regime: cc = clear-cut, sh = shelterwood cut. Site fertility index as used in German forest site classification: A = poor, Z = quite poor, M = medium fertile, K = fertile).

Management strategies	Fertility	Tree species: present/ future	Harvesting: rotation period length/ harvesting system	Thinning: intervall[1]/ intensity[2]
MS1[3] (conservation strategy) - all management interventions are excluded	all	all	-/-	-/-
MS2[4] (business as usual - BAU) - past MS - tree species composition are kept at the actual level and stands are managed with a low thinning intensity and the clear-cut system	all	Pine/pine	120/cc	10/0.9
		Oak/oak	200/cc	
MS3[4] (new management guidelines I) - stands on medium fertile and fertile sites are regenerated with oak using the shelter-wood system	A, Z	Pine/pine	140/cc	10/0.8
		Oak/pine	180/cc	
	M, K	Pine/oak	140/sh	
		Oak/oak	180/sh	
MS4[4] - production of pine timber in short rotation plantation with intensive thinning (possible use as energy wood)	A, Z	Pine/pine	100/cc	7/0.7
	M, K	Pine/pine	80/cc	
	all	Oak/pine	140/cc	
MS5[4] (new management guidelines II) - stands only at fertile sites are regenerated with oak using the shelter-wood system	A, Z, M	Pine/pine	120/cc	7/0.8
	Z, M	Oak/pine	160/cc	
	K	Pine/oak	120/sh	
		Oak/oak	160/sh	
MS6[4] - production of pine timber - sawn wood	all	Pine/pine	120/cc	10/0.7
		Oak/pine	200/cc	

[1]Thinning interval in years

[2]Thinning intensity is based on the stand density index

[3]All dead wood remains in the stand

[4]Slash from brushing and tending and dead trees with a breast height diameter < 15 cm (over bark) remain in the stand

4.1.6 Multi-criteria analysis

Alternative MS were evaluated with respect to a set of management objectives and different stakeholder priorities under current climate and climate change using a MCA method. The method used in this study was based on an additive utility model similar to that used in other studies (Kamenetzky 1982; Lexer 2000; Vacik and Lexer 2001; Kangas and Kangas

2002).

Decision hierarchy

The overall objective of the study was to identify the best MS for the Kleinsee management unit from a set of management alternatives. As a first step, the decision problem was hierarchically structured with representatives of forest stakeholder groups at a workshop organised in collaboration between the Potsdam Institute of Climate Impact Research and the Landesforstanstalt Eberswalde, the regional forestry research institute in Brandenburg (Welp et al. 2006). Four hierarchical levels were defined (Figure 4.1): overall objective (first level), partial objectives (second level), and measurable criteria of the partial objectives (third and fourth level). Partial objectives and their subordinated decision criteria were chosen under the constraint that the required decision criteria can be provided by the forest growth model 4C.

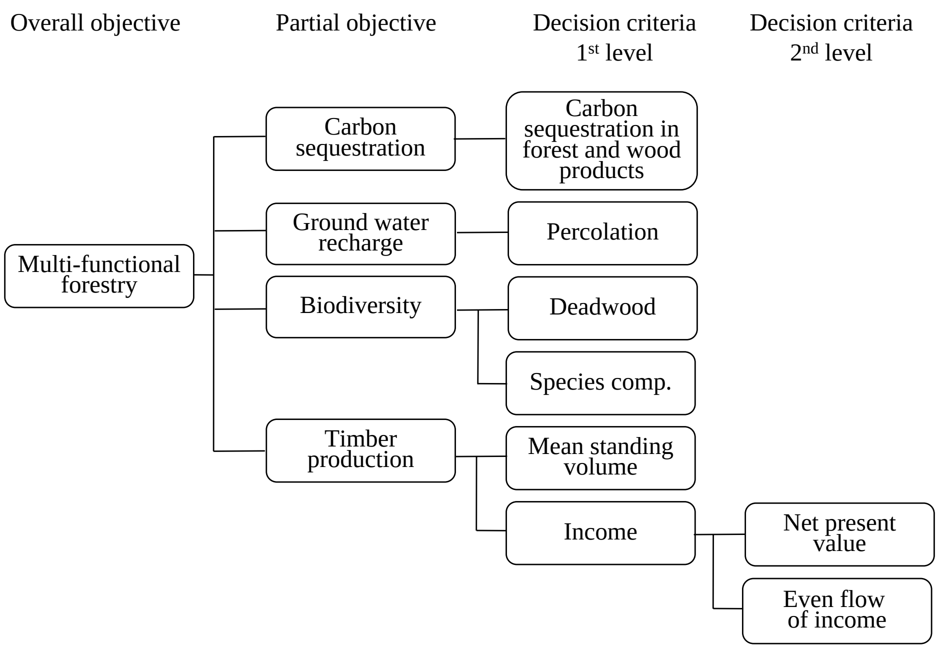


Figure 4.1: Decision hierarchy at Kleinsee.

Estimation of priorities

The relative priority of the partial objectives and decision criteria in respect to the parent element in the hierarchy was calculated using the pair-wise comparison technique of the Analytic Hierarchy Process (Saaty 1977). A questionnaire was handed to all participants of the stakeholder workshop and additionally distributed by mail to other stakeholders in which they were asked to compare two partial objectives at a time on a verbal scale of relative importance. This verbal comparison was later transformed into a corresponding score (Saaty 1977). Saaty's Eigenvalue method was used to calculate the priority of the elements in the pair-wise comparisons (Saaty 1977). In the study, three stakeholder groups were distinguished: forest manager of public-owned forest (FM), private forest owner

(FO), and environmental organisations (EO). FM and FO both pursued the main goal to produce income from forest management, however, the priority of this goal was higher for FO than FM (Figure 4.2). The other three objectives were considered of lower priority but the ranking differed between FM and FO. The representatives of the EO focused on a balanced supply and management of all forest functions.

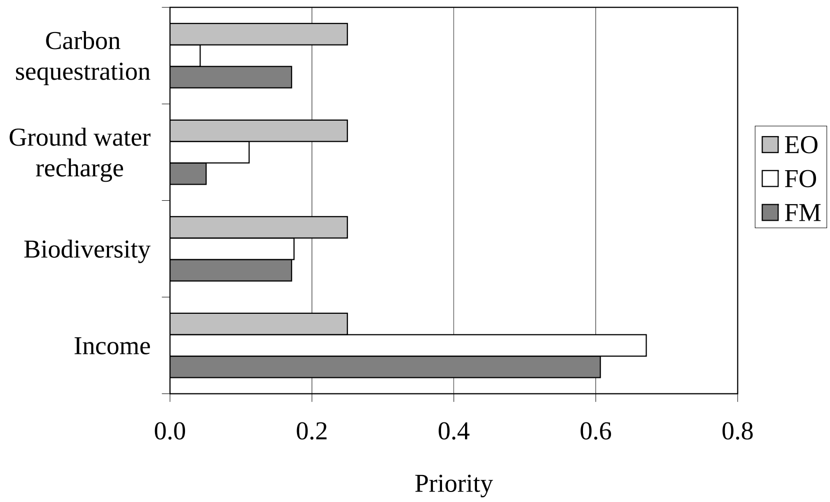


Figure 4.2: Preferences of the partial objectives determined by three stakeholder groups: forest manager of public-owned forest (FM), private forest owner (FO), and environmental organisations (EO).

The priorities of the decision criteria were quantified in cooperation with forest service personnel (Table 4.4) and used in identical form for all stakeholder groups.

Table 4.4: Relative priorities of the decision criteria.

Partial objective	Criteria first level	Priority	Criteria second level	Priority
Carbon sequestration	Carbon sequestration	1.00		
Ground water recharge	Ground water recharge	1.00		
Biodiversity	Dead wood	0.50		
	Species composition	0.50		
Income from timber production	Income	0.67	Net present value	0.67
			Even flow of income	0.33
	Mean standing stock after 100 years	0.33		

Application at unit level

The overall utility ($U_{s,c}$) of a MS (s) under a climate scenario (c) was calculated by an additive utility function, aggregating the weighted utilities of the partial objectives (Eq. 4.1), where a_i is the relative priority and $U_{s,c,i}$ the utility from the partial objectives (i). The overall utility can be seen as a measure of how well management meets the expectations regarding the objectives.

$$U_{total(s,c)} = \sum_{i=1}^{4} a_i \cdot U_{s,c,i} \quad \text{with the constrain:} \sum_{i=1}^{4} a_i = 1 \tag{4.1}$$

The utility from the partial objectives was calculated from the weighted summation of the utility values of the lowest-level criteria. Equation 4.2 was used if there was only one criteria level, and Eq. 4.3 was applied if there were two criteria levels. The parameters (m) and (o) are the number of chosen decision criteria at different levels of the hierarchy, $a_{i,j}$ and $a_{i,j,k}$ the relative weights respectively, and $u_{s,c,j}$ the associated lowest-level utility values for a management alternative (s) under climate scenario (c).

$$U_{s,c,i} = \sum_{j=1}^{m} a_{i,j} \cdot u_{s,c,j} \quad \text{with the constrain:} \sum_{j=1}^{m} a_{i,j} = 1 \tag{4.2}$$

$$U_{s,c,i} = \sum_{j=1}^{m} a_{i,j} \cdot \sum_{k=1}^{o} a_{i,j,k} \cdot u_{s,c,j} \quad \text{with the constrain:} \sum_{j=1}^{m} a_{i,j} = 1 \text{ and} \sum_{k=1}^{o} a_{i,j,k} = 1 \tag{4.3}$$

Utility functions

The utility for the lowest-level criterion (j) at unit level for the different MS are calculated from utility functions (Eq. 4.4) which convert the decision criteria values from its original measurement scale to the dimensionless scale [0, 1]:

$$u_{s,c,j} = f_j \sum_{l=1}^{43} R_l \cdot D_{s,c,j,l} \tag{4.4}$$

The criterion value (j) at unit level was calculated by summing up the area-weighted (R_l) criteria values ($D_{s,c,j,l}$) of the stand classes (l). The utility functions (f_i) were linear functions defined by supporting points (Eqs. B.1, B.2, B.3, B.4, B.5, see Appendix B) based on expert knowledge.

The carbon sequestration potential includes the mean annual carbon sequestrated in forests (living and dead biomass and soil), wood products, and landfills over the simulation period. A linear function is applied between the minimum and the maximum simulated carbon sequestration (Eq. B.1).

Forests currently contribute approximately 80 - 110 mm annually to the water balance in Brandenburg (Lahmer et al. 2000; Wechsung et al. 2004). A decrease in ground water recharge is forecasted under climate change (Lahmer et al. 2000; Suckow et al. 2002). It is of particular importance to at least maintain the current groundwater recharge and, furthermore, search for MS to increase ground water recharge. The four supporting points of the utility function reflect the decreasing importance of an additional increase in the percolation rate after securing the desired water supply (Eq. B.2). The utility value for ground water recharge was calculated annually and then averaged over the simulation time because the annual supply and its extreme values are more important for water management than a mean value over 100 years.

The amount of dead wood and the share of deciduous trees in an area were already used as criteria to assess the ecological values of forest ecosystems in other studies (e.g. Kangas and Pukkala 1996; Schuck et al. 2004). Dead wood was found to be important as habitat for fungi (Lindhe et al. 2004), insects (Hilt and Ammer 1994) and vertebrates in forest ecosystems (Maser et al. 1979). The total amount of carbon stored in dead wood was calculated in 4C. In the simulations the dead wood pool was initialised as 'empty' since there is hardly any dead wood in the Kleinsee stands; however, no actual dead wood inventory is available at this time. It is assumed that a certain amount of dead wood is necessary to provide habitat for species deepening on dead wood and a further increase of dead wood had a diminishing impact on biodiversity (Eq. B.3). The presence of deciduous tree species, especially oak, in forest ecosystems dominated by coniferous tree species, increases biodiversity and the self-regulation capacity of the forest ecosystem (Ammer and Schubert 1999; Majunke et al. 2004). Since oak needs a higher nutrient supply than pine, it is limited to the more fertile sites, whereas pine can also grow on poorer sites. The range of a preferable species composition was defined based on the target share of deciduous trees in the forest guidelines of Brandenburg (MELF (Ministerium für Ernährung, Landwirtschaft und Forsten) 1998) and the limitations implied by site conditions. A shift of the species composition to a less preferable mixture decreased the utility value (Eq. B.4).

The mean standing stock (MST) after 100 years was used as a proxy to evaluate the sustainability of forest management in coming decades. A utility value of 1 was defined for a mean standing volume that would occur under an even age-class distribution. This value was derived from a yield table. The utility value decreased if the MST fell below or rose above the target value (Eq. B.4).

Net present value was calculated to investigate the economic impact of forest management. The NPV is the discounted value (with discounting rate p) of the future expected net cash flow from forest management (C) over the simulation time (t) plus the discounted liquidation value of the standing stock at the end of the simulation time (L_{100}).

$$NPV = \sum_{t=1}^{100} \frac{C_t}{(1+p)^t} + \frac{L_{100}}{(1+p)^{100}} \tag{4.5}$$

The standard discounting rate used in this study was p = 0.02. According to the assumptions set for this study L_{100} was zero for young stands (pine < 30 years, oak < 50 years) and potentially could be negative or positive for older stands. The sensitivity of NPV was tested for different discounting rates (between 0.0 and 0.025) and alternative calculation methods for L_{100} (case 1 - L_{100} is calculated for all stands and positive and negative liquidation values are accepted; case 2 - L_{100} is calculated for all stands, but all negative liquidation values are set to zero). The utility function of NPV is a linear function between zero and the maximum NPV value (Eq. B.1). Negative values have a utility of zero.

The coefficient of variation (COV) of the cash flow over time periods of 20 years was calculated to roughly indicate how net returns of forest management are distributed over the simulation time. The utility function is inversely related to the COV (Eq. B.5). Under MS1, the utility values of the lowest-level criteria of the partial objective income from timber production are zero due to the definition that under this strategy there is no management for timber production.

4.2 Results

4.2.1 Simulation results

Carbon sequestration

The mean annual carbon sequestration in the study site Kleinsee ranged from 1.24 to 1.49 t C ha^{-1} a^{-1} under MS2 to MS6 and the CRU scenario (Figure 4.3a, Appendix B: Table B.2). The highest carbon accumulation under the CRU scenario occurred in managed stands under BAU (MS2), while the transient conversion to an oak dominated forest (MS3) sequestrated the least carbon. The carbon sequestration increased under the ECHAM4 scenario (up to +17%) and HadCM2 scenario (up to +27%) for MS2 to MS6. The conservation strategy (MS1) led to a considerably higher sequestration than any other MS due to the high amount of carbon stored in living and dead tree biomass under all climate scenarios, which exceeded the additional effect of carbon storage in wood products in the actively managed MS.

The distribution of sequestered carbon among the carbon pools differed considerably between the MS with and without timber harvests (Figure 4.3b, Appendix B: Table B.7). Soil was the main carbon sink for MS2 to MS6 (CRU: 0.84 - 1.30 t C ha^{-1} a^{-1}), followed by wood products, dead wood and living tree biomass which acted as a small carbon sink. In contrast, under conservation management (MS1) the standing stock, dead wood and soil contributed similar shares to the carbon sequestration. Under MS1 the wood product pool was found to be a carbon source.

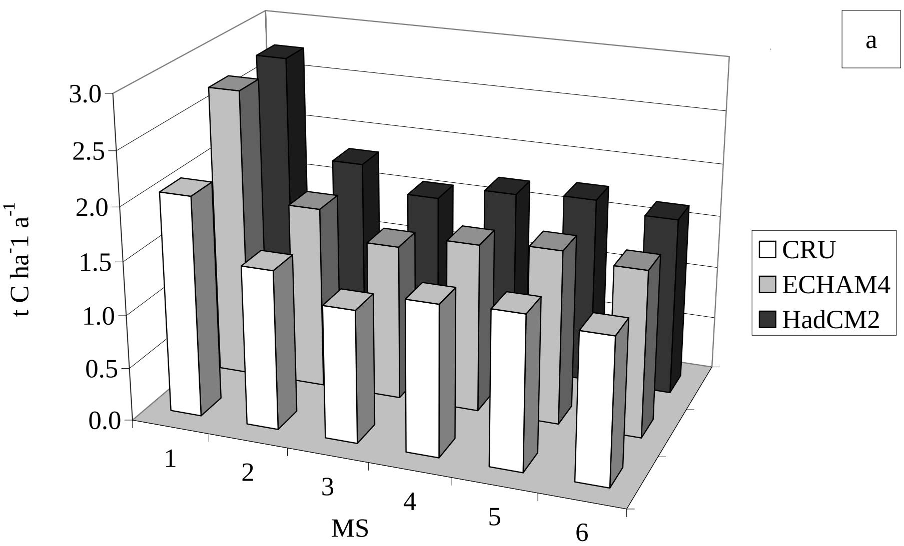
Ground water recharge

The mean annual percolation varied from 182 (MS4) to 213 mm (MS1). Percolation was positively influenced by conservation management (MS1) and an increasing proportion of oak (MS3). Under the climate change scenarios, percolation slightly decreased under all management regimes, except for MS3 under the HadCM2 scenario. In general, the decrease was more pronounced under the ECHAM4 scenario.

Biodiversity

The mean dead wood stock was highest without management (CRU 43.3 t C ha^{-1}), while active MS with thinning and harvesting stored less dead wood with only small differences among the MS (CRU: 10.1 - 13.1 t C ha^{-1}). No common pattern was found under the climate change scenarios - the mean dead wood stock slightly decreased or increased depending on the chosen MS (Appendix B: Table B.2).

Analysing species shares in the management unit under the different MS, the impact of initial species composition and age- class distribution became evident in addition to the influence of management. Even with a focus on pine plantations and a fast conversion as realised with MS4, a fraction of oak stands remained in the management unit after 100 years. The portion of pine stands after 100 years ranged from 92% (MS4) to 23% (MS3). Due to the fact that there were no climate-related transition to growth conditions completely unsuitable for pine or oak, the species distribution was not influenced by climate change.



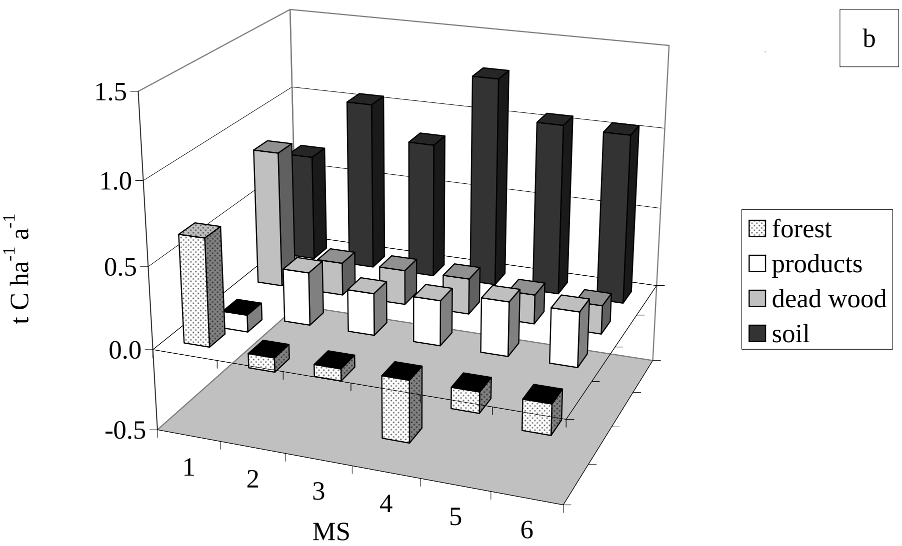


Figure 4.3: (a) The impact of management strategies (MS, compare Table 4.3) and climate scenarios on mean carbon sequestration over 100 years. (b) The effect of MS on the distribution of mean carbon sequestration among the carbon pools: soil, dead wood, forest stand, and products under the CRU climate scenario.

Income from timber production

Conservation management (MS1) led to an over-representation of old stands. Therefore, the MST after 100 years (CRU 480 m^3 ha^{-1}) greatly exceeded the MST in stands with active management (CRU 161 - 238 m^3 ha^{-1}). MS3 and MS4 led to a decrease of the MST compared to BAU by 32 and 17%, respectively, while the other MS with active management maintained a MST similar to BAU. The MST increased under both climate change scenarios (ECHAM4 showing smaller effects than HadCM2) with the strongest effects for MS3 and MS1.

The choice of the MS has a strong impact on NPV. Intensive thinning and a short rotation period (MS4) or the transformation to an oak dominated management unit (MS3) resulted in the lowest NPVs (604 € ha^{-1} and 484 € ha^{-1}, discounting rate $p = 0.02$). In contrast, a management regime with medium thinning intensity and rotation length and a high percentage of pine stands (MS5 and MS6) increased the NPV four to seven times compared to MS4 or MS3 (Appendix B: Table B.2). The climate change scenarios positively affected the NPV. Under the ECHAM4 scenario the increase was smaller than under HadCM2, except for MS3 where it was the reverse. The impact of climate change was most distinctive for MS3 as well as MS4 (increases of about 50%).

The COV of the cash flow over time periods of 20 years was mostly influenced by management and ranged from 55 to 147% for all scenarios.

4.2.2 Multi-criteria analysis - overall utility

Two different aspects can be evaluated studying the computed utilities and rankings of the MS with regard to overall utility: first, the impact of stakeholder priorities, and second, the impact of climate change. For the detailed results of the utility values of the lowest-level criteria see Appendix B.

Influence of the priorities of different stakeholder groups

The priority setting had the strongest influence on the overall utility of the MS, their range, and their ranking. The range of the overall utility under the priority setting of EO was small (CRU 0.17) compared to the range of the overall utility for FM and FO (CRU 0.38 and 0.41). The overall utility of all MS under the priority setting of FM depended strongly on the partial utility from timber production due to the high priority assigned to this objective. Therefore, differences among the MS occurred mainly due to differences in the related criteria (Figure 4.4a and Table B.8). Under MS5 and MS6 the highest overall utilities were obtained (CRU 0.70), followed closely by MS2. The lower partial utility of income from timber production under MS2 relative to MS5 and MS6 was almost offset by the high utility of the partial objective biodiversity. The high partial utility for biodiversity is achieved due to the considerably higher utility value for the criterion species distribution compared to the other MS with active management (Appendix B). The application of MS3 or MS4 is less preferable for FM (0.43 and 0.40) due to the low income under those management regimes. For FM, MS1 achieved the lowest utility. The higher partial utilities of carbon sequestration, ground water recharge, and biodiversity for MS1 could not compensate the loss in income from timber production.

The overall utility under the priority setting of FO is to a higher degree affected by the performance with regard to the partial objective income from timber production than the overall utility of FM (Figure 4.2). The ranking of the MS is similar to those of the FM (MS5 > MS6 > MS2 > MS4 > MS3 > MS1; Figure 4.4b and Table B.9). However,

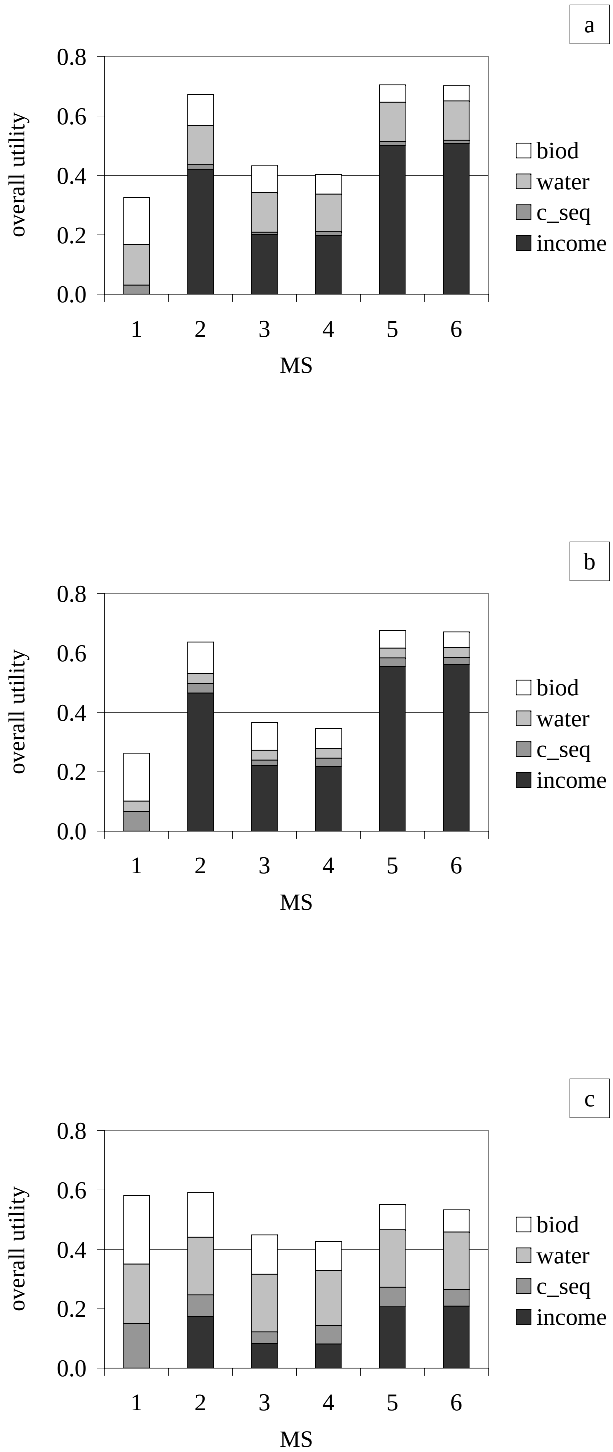


Figure 4.4: Overall and partial utilities (biod = biodiversity, water = groundwater recharge, c_seq = carbon sequestration, and income) of management strategies (compare Table 4.3) under the preference setting of (a) the forest manager of public-owned forest (FM), (b) the private forest owner (FO), (c) and the environmental organisation (EO).

in contrast to FM, carbon storage got a higher priority and therefore, MS5 is slightly preferred compared to MS6. MS3 and MS4 (0.36 and 0.35) were only half as preferable as MS5.

The main focus of EO was on a forest management scheme ensuring all forest functions equally. For this priority profile, MS2 provided the highest utility under current climate (0.60) closely followed by MS1 (Figure 4.4c and Table B.10). MS2 was characterised by a higher partial utility from biodiversity and carbon sequestration compared to strategies MS3 to MS6, the exception being that the partial utility from carbon sequestration was similar under MS5. The higher partial utilities from carbon sequestration and biodiversity under MS1 compared to MS2 were offset by the partial utility of income from timber production under MS2. The partial utility of ground water recharge was only slightly influenced by management, and therefore did not influence the ranking. MS3 and MS4 (0.45 and 0.43) achieved, as under all stakeholder scenarios, the lowest rank among the MS with active management.

Influence of climate scenarios on the overall utility

In general, both climate change scenarios increased the overall utility of the MS under all stakeholder priority profiles, but the effect was stronger under the HadCM2 scenario (Table 4.5). The increase of the overall utility varied among the stakeholder scenarios and MS. MS3 and MS4 benefit most under the climate change scenarios through a strong increase of the partial utility of income from timber production. Therefore, the highest increase of the overall utility of MS3 and MS4 was found under the priority profile of FO. Under the HadCM2 scenario and the preferences of FM and FO respectively, the ranking of MS3 and MS4 switched, but the overall utilities were still very close. The increase of the overall utility of MS2, MS5 and MS6 was small under the climate change scenarios (FM $<$ 4%, FO $<$ 6%, and EO $<$ 8%). Under MS1 the increase in the overall utility is due to a strong increase of carbon sequestration in the forest. Thus, the influence of climate change on the overall utility of MS1 is the highest under the priority setting of EO. This led to a change in ranking between MS1 and MS2 compared to the results under the CRU scenario. While MS2 was the most preferable MS under the CRU scenario, MS1 was the most preferable MS under both climate change scenarios.

Table 4.5: Overall utility of all management strategies (MS, compare Table 4.3) for all stakeholder preference profiles and climate scenarios (c = CRU, e = ECHAM4, h = HadCM2). Bold letters indicated the MS with the highest overall utility.

Stakeholder group	Climate scenario	MS					
		1	2	3	4	5	6
Forest manager of public-owned forest	c	0.33	0.67	0.43	0.40	**0.70**	**0.70**
	e	0.34	0.71	0.54	0.51	**0.74**	**0.74**
	h	0.34	0.72	0.53	0.54	**0.75**	**0.75**
Private forest owner	c	0.26	0.64	0.37	0.35	**0.68**	0.67
	e	0.30	0.69	0.49	0.47	**0.73**	0.72
	h	0.30	0.70	0.49	0.50	**0.74**	0.73
Environmental organisation	c	0.58	**0.59**	0.45	0.43	0.55	0.53
	e	**0.66**	0.63	0.52	0.49	0.58	0.57
	h	**0.67**	0.65	0.54	0.52	0.61	0.59

4.2.3 Sensitivity with regard to discount rate and liquidation value of NPV

A sensitivity analysis of the NPV calculation revealed that the discounting rate (p) has a strong influence on the NPV under all MS (for an example see Figure 4.5). However, the overall utility and the ranking of the MS with regard to NPV were not sensitive to variations in p. For MS1, MS2, MS5, and MS6, a change in the discounting rate resulted in a change of less than 1% of the overall utility compared to the results of the baseline discounting rate (p = 0.02) for all scenarios (climate change and stakeholder preferences). For MS3 and MS4, the overall utility decreased with increasing discounting rate but to a higher degree for MS4. As both MS have a similar overall utility this change led to a rank reversal (Figure 4.6) or convergence of the ranking depending on the climate scenario and stakeholder preferences.

The NPV (p = 0.02) is not very sensitive to the chosen calculation method of the liquidation value (L_{100}). For the MS with active management the L_{100} varies at most by 4% between the standard calculation method and their alternatives (see Section 4.1.6) except for MS3 were the variations are higher. This is due to the fact that young oak stands yield negative liquidation values for a longer period relative to other stand types.

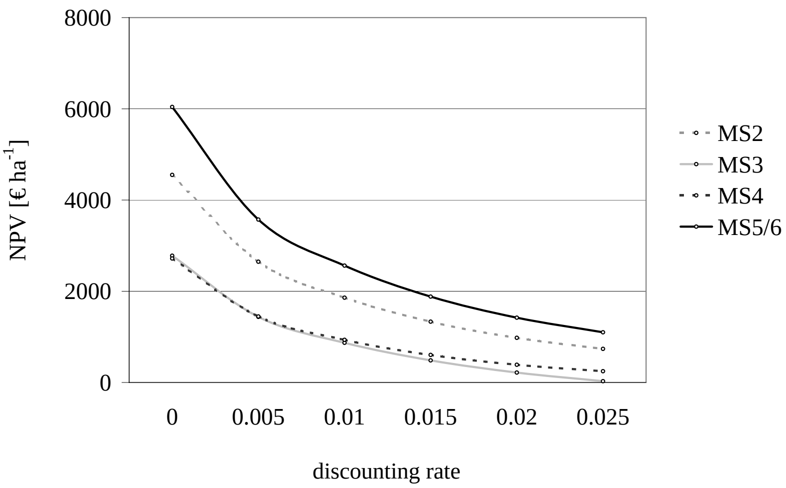


Figure 4.5: Sensitivity of the net present value to the discounting rate under management strategies MS2 to MS6 (compare Table 4.3) and the CRU climate scenario.

4.3 Discussion

The impacts of forest management and climate change on forest functions were analysed for a real forest management unit. Differences between management options were influenced by the current forest conditions (e.g. species composition and age structure) and the chosen planning horizon. Therefore, the discussion evaluates differences in the simulation results between MS occurring in a specific transient situation (Sections 4.3.1 and 4.3.2) taking

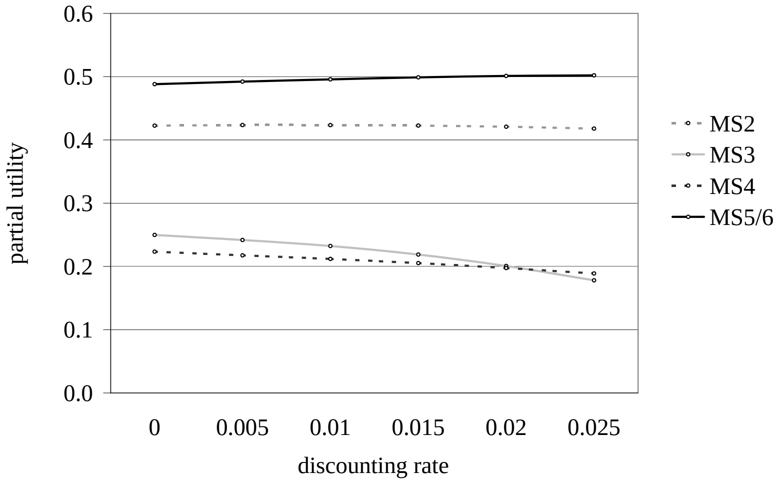


Figure 4.6: Sensitivity of partial utility from objective "income from timber production" to the discounting rate for the management strategies MS2 to MS6 (compare Table 4.3) under the preference setting of the forest manager of the public-owned forest (FM) and the CRU climate scenario.

into account limitations in transferring the findings to other forest areas. Furthermore, advantages and limitations of the MCA application in the Kleinsee study are addressed (Section 4.3.3) evaluating the projections of stakeholders on potential future benefits and risks of forests management (Section 4.3.4).

4.3.1 Impact of forest management on forest functions

Impact of forest management on forest functions

The unmanaged forest accumulates more carbon in biomass than managed forests as also reported in earlier studies (Kramer 1988). In this study the carbon sequestration trend may be slightly overestimated because losses through biotic and abiotic disturbances (e.g. diseases, storms, and wild-fires) are not included in the applied model. However, it must be stressed that only a one-time non-permanent increase in carbon storage in living biomass is achieved with these measures. Even if the soil and the wood products pool are included in the analysis the high carbon storage in biomass of the unmanaged forest was not fully compensated under any of the actively managed strategies. In order to achieve a comprehensive evaluation of the impacts of climate and management at the management unit level, in terms of climate protection aims, the substitution of fossil fuels through forest biomass as renewable energy source and the substitution of materials with an energy intensive production through wood prodcuts has to be additionally taken into account (e.g. Werner et al. 2005). The overall climate protection effect for managed forest would then increase in comparison to non-managed forest (Marland and Schlamadinger 1997).

Ground water recharge

To maintain the ground water recharge in southeast Brandenburg especially under the perspective of climate change, the increase of the share of oak stands and the conservation of current stands could be recommended. Oak stands have lower evapotranspiration rates during wintertime compared to pine since they shed their leaves. Under the conservation management there is a transient trend to old stands with decreasing transpiration due to opening of the crown cover compared to middle-aged stands (Müller 1996). This trend seems to exceed the advantages of young stands with high percolation rates in managed forests with an even age class distribution. However, differentiation in percolation between the MS may be more pronounced when the impact of management on ground vegetation would be taken into account. The evapotranspiration rate of ground vegetation in pine forests can be up to 35% of the precipitation, depending on the abundance and species composition of the ground vegetation (Müller 1996) which is controlled indirectly by management through changes in the light regime in the stands (Bolte 1996) and the tree species composition.

Biodiversity

Today's species composition in Kleinsee is close to the species mixture which is assumed to be optimal in this study. There is a large portion of autochthonous oak stands which were preserved from exploitation due to the remote position of Kleinsee (Krausch 1957). MS1 and MS2 benefit from the preferable current situation. But if the management unit currently would be stocked with almost pure pine forests the ranking of the MS with respect to biodiversity aspects would completely change. MS that convert pine to oak stands (MS3 and MS5) would then be the most preferable strategies. The ranking among the other MS would then depend on the amount of dead wood, for which MS1 obtains the highest value.

Income from timber production

In contrast to many other economic sectors forestry uses a resource and simultaneously maintains the forest ecosystem and its functions. These services of forestry are not reimbursed and most income for forest owners comes from timber production. Pine forests are most profitable at Kleinsee in this study. Oak stands have the disadvantage of a longer rotation time and lower biomass productivity. In short rotation management the lower profit for small dimension logs can not be compensated by the shorter production time.

However, next to the relatively small uncertainties of the calculated NPV due to difficulties in monetary evaluation of young stands and the choice of the discounting rate (see Section 4.2.3), high uncertainty is associated with the NPV values due to the future development of harvesting cost and timber prices. Harvesting cost will be influenced by factors such as increasing labour costs, rationalisation of timber harvesting, and improved harvesting technology influencing in turn harvesting costs. The timber prices will probably increase, but the relation of the prices between wood species and assortment classes is uncertain too due to changing demands on the timber market. Under this restrictions it can be concluded that forest management in Kleinsee is barely profitable under the current price and growth conditions. This raises the question of how to assure the continuation of desirable forestry operations based on societal demands for forest services.

Trade-offs between forest functions under different management strategies

Evaluating trade-offs between single forest functions under different management alternatives can lead to a better understanding of the advantages and disadvantages of those management alternatives. Exemplary trade-offs due to changes in MS are discussed in comparison to the BAU management (MS2) under the CRU scenario. An increase of the NPV by about 440 € ha^{-1} (50%) over the planning period could be achieved by applying MS5 or MS6. But this leads to a reduction of carbon sequestration by 0.05 or even 0.12 t C ha^{-1} a^{-1} (4% or 9%) and conversion to a highly pine dominated management unit. In contrast, searching for the possibility to increase the ecological and climate protection function of the forest ecosystem, the best MS is to protect the forest from management interventions. However, this means to sacrifice a NPV of almost 1000 € ha^{-1} for an increase in carbon sequestration of 0.57 t C ha^{-1} a^{-1} and a high share of dead wood. Compared to BAU a conversion to short rotation pine stands (MS4) or an increase in the share of oak (MS3) has no advantages except an increase in ground water recharge (MS3). In this way only trade-offs between single forest function can be analysed, but for a comprehensive analysis the MCA is necessary (see Section 4.3.4).

4.3.2 Impact of climate change on forest functions

The increase of forest ecosystem productivity in the Kleinsee region (Figure 4.3a) under the impacts of a possible climate change and increasing levels of CO_2 is in line with results reported in earlier studies (Kellomäki and Leinonen 2005; Kramer and Mohren 2001; Kellomäki et al. 2000). In the temperate forests an increase in temperature, coupled with increasing precipitation, usually results in increasing productivity. Strong drought effects lead to reduced productivity. If growth reductions due to the temperature and precipitation effects occurred in this study they are offset by the CO_2 fertilisation effect (Lindner et al. 2005). Hence the impact of the climate change scenarios on forest functions in this study is dominated by the strong positive effect on carbon sequestration and income from timber production, while the negative effects - a decreasing percolation rate and amount of dead wood - are only small.

However, it must be stressed that precipitation scenarios in the continental east of Germany are subject to high uncertainties, with GCM scenarios including increasing as well as decreasing precipitation levels (IPCC 2001). Other studies on the effect of climate change and increasing CO_2 levels on forest productivity for the north-eastern German lowlands and Brandenburg reported also losses in productivity (Lasch et al. 2002; Gerstengarbe et al. 2003). Thus, if a stronger reduction in precipitation is assumed under climate change than in the applied climate change scenarios, especially oak may show reduced growth (Lindner et al. 2005). Furthermore, the climate change scenarios do not predict years with climatic extreme events such as the dry, hot summer of 2003 that led to major losses in NPP across Europe (Ciais et al. 2005). In effect, the losses due to possible drought events may be underestimated applying the available climate change scenarios.

4.3.3 Advantages and limitations of multi-criteria analysis

Silvicultural decisions in multi-purpose forestry are very complex and the impact of different MS on various functions is difficult to quantify at a glance. In this study, MCA provides an effective tool to support and evaluate the decision process. The structure of the decision problem with partial objectives and measurable criteria (Lexer 2000; Mendoza and Prabhu 2000a) is easy to derive and allows to involve stakeholder groups in the decision process (Mendoza and Prabhu 2000a; Munda 2004). The pair-wise comparison technique (Saaty 1977) provides an effective method to estimate relative stakeholder priorities. Furthermore, MCA allows to combine subjective priorities of involved stakeholders and expert knowledge (necessary to define the lowest-level criteria and their evaluation) in the decision process.

One should be aware that the hierarchical structure, the choice of criteria and utility functions directly affects the evaluation results of the MCA. The number of criteria under each partial objective and their hierarchical level influences the weight of a single criterion in the additive utility model. Increasing the degree of detail through additional hierarchical levels and a high number of criteria decreases the sensitivity to changes in individual decision criterion values. Therefore the number and hierarchical level of the criteria needs to be chosen keeping in mind the structurally inherent impacts on the results. Wolfslehner et al. (2005) recommend an alternative use of the Analytic Network Process (Saaty 2001) where the individual weight of a criterion is less affected by the given model structure. In the present study, the utility functions use simplified relationships between the unitless utility scale and the respective lowest-level criterion value. However, more complex, non-linear utility functions can be used if sufficient information is available.

4.3.4 Impact of different stakeholder interests

The MCA allows to compare alternative MS on the basis of the overall utility. Furthermore trade-offs can be studied in the search for a MS which meets the expectation of different stakeholder groups on forest management. In the Kleinsee study FM and FO (pursuing the main objective to gain income from timber production) and EO (with the main focus on a balanced management of all forest functions) prefer different management regimes (Figure 4.4a-c). However, under the given conditions a compromise in forest management between the stakeholder groups seems possible. For instance, the BAU treatment (MS2) realises a high timber production, carbon sequestration, and biodiversity. For the EO this MS is already the most preferable management alternative under the CRU scenario. For FM and FO this management regime does not achieve the highest overall utility but the overall utility is only slightly lower than that of MS5 (MS with the highest utility, Table 4.5). One way to achieve a similar utility for MS2 as for MS5 under the priority setting of FM or FO and the current climate scenario would be an adjustment payment increasing the NPV of the simulation period (FM: + 71 € ha^{-1}, FO: + 85 € ha^{-1}). A different option to meet the expectations of all stakeholder groups is a mix of different management strategies at the management unit level as typical in forest management practice. The hypothesis that a mixture of MS will increase the overall utility of a management unit is supported by the following facts. The utility value with regard to a single criterion can in most cases only be maximised by a combination of MS in the management unit. The ranking of the utility values can differ in stands with similar tree species and age but different soil type and fertility.

The results presented in this section are only valid for the considered region with its specific forest conditions. For instance, in a management unit currently dominated by pine monocultures the EO may prefer a treatment that changes the species composition to achieve a more close-to-nature situation in the unit. However, we are convinced that the combination of process-based forest ecosystem models and multi-criteria analysis methods are an efficient tool to support planning and decision making of adaptive forest management under conditions of climate change.

Acknowledgments

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Chapter 5

Effect of material and energy substitution on the effective source/sink function of managed forests

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Abstract

Forestry and especially the wood product sector contribute to the reduction of atmospheric carbon and other greenhouse gases. Carbon is sequestrated in living and dead biomass, soil, and wood products in use and in landfills. Wood products can substitute equivalent products made by other materials, which in most cases are more energy intensive during their life cycle. Furthermore, harvesting residues, industrial waste wood, and wood products at the end of their life cycle can be incinerated and substitute fossil fuels. In contrast to the carbon pools in the forest sector and wood product sector, which can act as a sink but can also be neutral or a source, the substitution effect continually reduces carbon emission as long as forests are managed and timber is harvested.

This study quantified the effect of carbon sequestration in the forest sector and the wood industry sector plus substitution effects under different management strategies at three local scales: management unit level, the federal state of Brandenburg, and Germany over 50 years. To achieve this objective, the carbon emission reduction potential of material and energy substitution (S_{mat} and S_{en}) were estimated based on data gathered in other studies. Carbon sequestration and substitution effects were simulated using the forest growth models 4C (management unit level) and EFISCEN (Brandenburg and Germany) and a wood product model (WPM). An investigation was conducted on the influence of uncertainties in the initialisation of the WPM, S_{mat}, and basic conditions of the wood product sector on carbon sequestration plus substitution effects. Results showed that the wood industry sector offers the main climate change mitigation potential. Its carbon sequestration plus substitution effects exceeded sequestration in the forest sector, in some cases by up to three times. Energy substitution accounted for about half of the total carbon sequestration plus substitution effects, followed by carbon storage in landfills. In Germany the absolute

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annual carbon sequestration in the forest and the wood industry sector plus substitution effects was 19.9 Mt C. The wood industry sector contributed 70% of the total carbon sequestration plus substitution effects.

5.1 Introduction

Ongoing climate change raises concerns about adverse effects on people's the livelihoods throughout the world (IPCC 2001, 2007) and has led to international efforts to establish climate protection policies, activities and contracts (e.g. United Nations Framework Convention on Climate Change (UNFCCC)). Forest ecosystems, as well as the wood industry sector, facilitate possibilities to reduce greenhouse gas (GHG) emissions. Afforestation and forest management in existing forests ecosystems can lead to increasing carbon stocks in the biosphere. Both effects of forest management are accounted for under Articles 3.3 (afforestation, reforestation and deforestation) and 3.4 (forest management) of the Kyoto Protocol, but many climate protection options within the whole forest and the wood industry sector result from the use of wood products and are accounted for in other sectors (e.g. industry). Thus, forest management options that are used under the umbrella of the Framework Convention can, in general, be evaluated with respect to their contribution to the objective of stabilisation of the GHG concentrations, but their effects are accounted for in different sectors and at different scales. Thus, full accounting of carbon exchange within the atmosphere is only achieved at the scale of the entire UNFCCC and Kyoto Protocol objectives; however, there is a trade-off between the forest and the wood industry sector. Increased stocks in forests may reduce the use of wood products and thereby reduce substitution effects. In this case, the overall effect may even lead to an increase in the atmospheric carbon content even though an Article 3.4 measure is successful.

Carbon is sequestrated in the forest ecosystem within living and dead biomass and soil. After timber harvest, most of the carbon that was in living biomass is no longer stored in the forest ecosystem, but the timber is used in multiple wood products such as paper, packing material, furniture, construction timber, and also for energy production. During their lifetime, wood products store carbon and therefore provide a temporary sink, especially wood products with a long lifespan (Werner et al. 2005). After the first use, many wood products can be recycled for use in lower quality products. But wood products not only accumulate carbon; they can also positively affect the global carbon cycle by substituting for other, usually more energy-intensive materials such as concrete or steel (e.g. Burschel et al. 1993; Petersen and Solberg 2005; Werner et al. 2005). This is known as material substitution. At the end of their life cycle, wood products can be incinerated for energy production and therefore be a substitute for fossil fuels, which is referred to as energy substitution. In addition, wood not suitable for industrial purposes (small dimension timber, low quality timber, harvesting residues, or wood waste accruing during production processes) can also be used for energy purposes. Thus, in the overall perspective, wood products contribute in three ways to the reduction of the atmospheric carbon content: (i) carbon storage in products, (ii) reduction of carbon emissions by material substitution, and (iii) reduction of carbon emissions by energy substitution. These cross-sector effects between forestry, the timber industry, and other industries may create an incentive not to focus on Article 3.4 alone but rather to invest resources in a system that manages the sources and sinks related to the forest ecosystem and the use of wood across the whole forest/wood chain.

The overall objective of the current study was to investigate the carbon sequestration in the forest and wood products sector plus the effects of material and energy substitution in order to quantify and demonstrate the importance of an overall examination in the discussion of the climate protection potential of forest ecosystems. For this purpose, the mean annual carbon sequestration over the simulation time was calculated for the forest and the wood industry pools including soil, living and dead biomass, wood products in use and in landfills. The mean annual effect of material and energy substitution on the reduction of carbon emissions was calculated by adding up the annual emission reduction and division by the length of the simulation period. The effect of forest management on carbon sequestration in the forest and the wood industry sector plus substitution effects was illustrated at three different scales: (i) forest management unit level, (ii) federal state of Brandenburg, and (iii) Germany. We used the forest growth simulation models 4C and EFISCEN to analyse the carbon sequestration in the forest ecosystem and a wood product model (WPM) to assess wood products. The estimator of carbon emission reduction by material substitution ($S_{mat,C}$) is based on a literature review of studies comparing environmental impacts of wood products and their functional equivalents (e.g. Richter et al. 1996; Künniger and Richter 2001; Petersen and Solberg 2005). Based on these studies, an investigation was also conducted on the reduction potential of GHGs. As far as information was available, GHGs including CO_2 were considered a form of CO_2-equivalents. A separate analysis of a single GHGs was not possible due to the lack of detailed data. Carbon emission reduction through energy substitution was of further interest.

In the current study, special focus was set on four objectives. First, the potential of carbon emission reduction by energy and material substitution and the carbon sequestration in wood products in use and in landfills was investigated under different management strategies. Second, the impact of uncertainties in the initialisation of the WPM and in the calculation of $S_{mat,C}$, the effect of changing basic conditions such as changes in waste removal regulations, and the possible impact of the consideration of additional GHGs on the climate protection function of wood products was analysed. The third objective was the investigation of carbon sequestration in the forest sector. Finally, the overall effect of carbon sequestration in the forest and the wood industry sector plus substitution effects was compared between managed forests and forests under conservation and quantified in absolute figures for Germany.

5.2 Methods

5.2.1 Data

Material substitution

Material substitution refers to the possible use of products mainly composed of wood (wood products) in place of products composed of another main material, such as steel, concrete, or PVC (equivalent products). Wood products and their equivalent products possess similar technical characteristics. Wood products and their equivalent products were compared in terms of carbon emissions and GHG (including CO_2) emissions during their life cycle. The effect of material substitution on carbon ($S_{mat,C}$) and GHG emissions ($S_{mat,GHG}$) was quantified in tonnes of carbon equivalents per tonnes of carbon in used wood (t C (t C)$^{-1}$), where $S_{mat} > 0$ indicates a reduction of the emissions to the atmosphere when wood is used instead of equivalent materials.

For the calculation of $S_{mat,C}$ and $S_{mat,GHG}$ studies were selected which met two requirements: (i) the amount of wood used per production unit (e.g. one window, 1 m^2 flooring) was known and (ii) information about primary energy consumption, carbon emissions, or GHG emissions was available at least for the production process. We did not include short-lived wood products. For some of these products, an equivalent product does not exist (e.g. tissue, writing paper) whereas, for others (e.g. packing material) insufficient data was found to compare wood and an equivalent product. This resulted in a conservative estimate of $S_{mat,C}$ and $S_{mat,GHG}$.

Data preparation $S_{mat,C}$ and $S_{mat,GHG}$ were calculated at least for the production phase and, if the data was sufficient, for the entire life cycle including extraction of resources, production, use, and destruction of the products. The effect of recycling was excluded in the calculation of $S_{mat,C}$ and $S_{mat,GHG}$ because it was accounted for in a separate part of the WPM (see Section 5.2.2). If a study analysed different variants of products of the same main material, the standard option of the wood product and its equivalent product were compared and this figure was used for further analysis. If no standard option was specified, the mean of the variants was used for the analysis. In most studies, information on carbon and GHG emissions were only given for the whole product but not the single components. Therefore, carbon and GHG emissions were fully attributed to the amount of wood in a wood product even if it contained low amounts of other materials. On the other hand, low amounts of wood found in the equivalent product were not taken into account when calculating $S_{mat,C}$ and $S_{mat,GHG}$.

Initially the difference of carbon emissions (ΔC) between equivalent product (C_{equ}) and wood product (C_{wood}) was calculated in tonnes C per production unit:

$$\Delta C = C_{equ} - C_{wood} \tag{5.1}$$

If the amount of carbon emissions was not given in the studies, the primary energy consumption of the products (in GJ per production unit) was used to calculate ΔC. Primary energy is energy contained in raw fuels and any other forms of energy that are used as input throughout the life cycle of a product. The primary energy consumption was differentiated in energy from renewable sources and other energy sources. If no details were reported in the studies, a share of 25% of renewable energy was assumed in the production phase of wood products based on studies by Künniger and Richter (2001) and Wegener and Zimmer (2001). The share of renewable energy for equivalent products was 2.7%, which is equivalent to the share of renewable energy in the German energy mix (AGEB (Arbeitsgemeinschaft Energiebilanzen e.V.) 2003). Due to the lack of data, no distinction was made between electricity and heating energy. The difference in primary energy consumption (only from non-renewable sources) between the equivalent product and the wood product (P_{equ} and P_{wood}) was calculated and converted into carbon emissions using the factor E_C:

$$\Delta C = (P_{equ} - P_{wood}) \cdot E_C \tag{5.2}$$

where E_C was the amount of carbon emission per GJ primary energy and equalled 0.0153 t C GJ^{-1}. E_C was calculated from the specific primary energy mix in Germany in 1999, without renewable energy sources (AGEB (Arbeitsgemeinschaft Energiebilanzen e.V.) 2003: 39.1% mineral oil, 21.2% mineral gas, 13.7% anthracite, 13.0% nuclear energy, and 10.3% lignite). This factor only concerned emissions during the production process of primary energy. Other emissions during the life cycle of primary fuels and other energy sources such as those from mining, transportation, or construction of energy plants were not considered in the study.

The difference in GHG emissions (ΔG) between equivalent product (G_{equ}) and wood product (G_{wood}) was calculated in tonne carbon equivalents per production unit. The difference between G_{equ} and G_{wood} (both given in tonnes CO_2 equivalents per product unit) was converted into tonnes carbon using the factor 0.273 (mass ratio C:CO_2):

$$\Delta G = (G_{equ} - G_{wood}) \cdot 0.273 \tag{5.3}$$

To calculate $S_{mat,C}$ and $S_{mat,GHG}$, ΔC and ΔG were further divided by the amount of timber used in the wood product (T) given in tonnes carbon per production unit:

$$S_{mat,C} = \frac{\Delta C}{T} \tag{5.4}$$

$$S_{mat,GHG} = \frac{\Delta G}{T} \tag{5.5}$$

For this purpose the amount of timber (T) in wood products, originally given in volume (m^3 per production unit) or mass (tonnes per production unit), was consistently converted into tonnes carbon per production unit using the following conversion factors:

(i) wood density: 0.44 g cm^{-3}

(ii) carbon content: 50% by oven-dry mass

The wood density was based on two figures: (i) mix of sawn timber typical for Germany (75.5% coniferous and 24.5% deciduous trees) and (ii) wood density of conifers (0.41 t m^{-3}) and deciduous trees (0.54 t m^{-3}; UN-ECE/FAO 1992).

Aggregation of the reviewed studies The data from the single studies were aggregated at three levels to calculate $S_{mat,C}$: wood product, wood product class, and wood product sector (Figure 5.1). First, at wood product level, the material specific values of $S_{mat,C}$ of each product were calculated by averaging the results of different studies. Then, the material specific values of $S_{mat,C}$ of each product were averaged to derive the $S_{mat,C}$ of the product. An exception was made for the calculation of the $S_{mat,C}$ of windows because the share of different material was known (Fenster1 2005). The main materials for window production, in addition to wood (22%), were PVC (55%), and aluminium (19%). No detailed information was given for the other materials. $S_{mat,C}$ of windows was calculated by a weighted $S_{mat,C}$ for the substitution of windows composed of PVC (70.5%) aluminium (24.4%) and other materials (5.1%).

Woods products were classified in three classes: (1) buildings, (2) building components, and (3) exterior constructions. No sufficient data was found for furniture. For the calculation of $S_{mat,C}$ of wood product class 2 and 3, it was assumed that the wood products contributed different shares to the product class. Therefore $S_{mat,C}$ of wood products were weighted by the estimated share of the products in the class based on data by Scharai-Rad and Welling (1999) and Jaakko Pöyry Consulting (2002) (Figure 5.1) and then summed up. The last aggregation level was the product sector level including the building sector and exterior construction sector. Concerning the building sector, the reviewed studies contained information about single building compartments and whole buildings. $S_{mat,C}$ of the building sector was the mean value of both wood product classes; however, building compartments were also part of buildings. $S_{mat,C}$ of the exterior construction sector was identical to the same named wood product class (exterior construction). The overall $S_{mat,C}$ of wood products was derived from the weighted summation of the $S_{mat,C}$ of both sectors. Based on Scharai-Rad and Welling (1999) and on studies reviewed by Jaakko Pöyry Consulting (2002), 87% of the sawn wood goes to the building sector and 13% to the exterior construction sector. $S_{mat,GHG}$ was calculated in analogy.

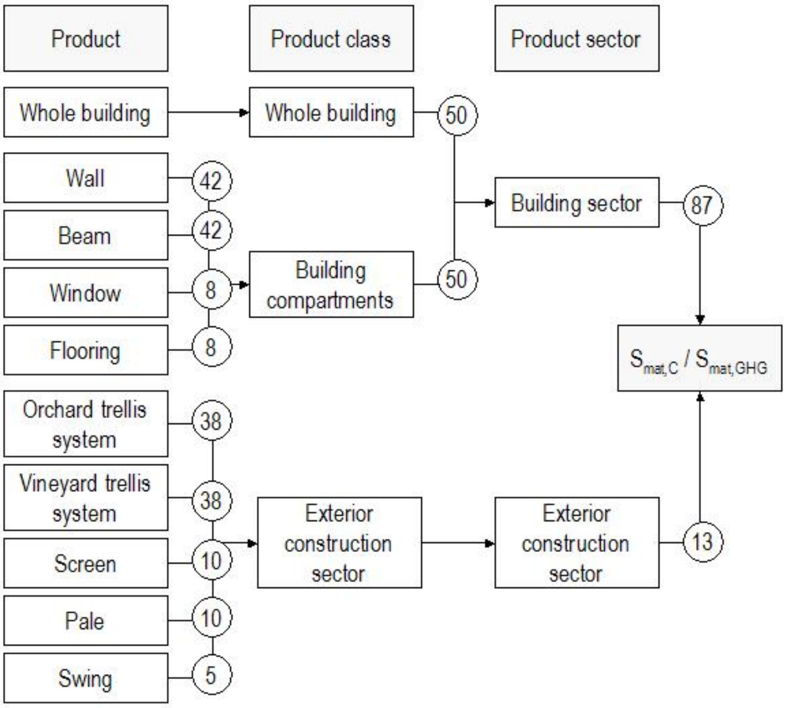


Figure 5.1: Aggregation scheme for the calculation of $S_{mat,C}$ and $S_{mat,GHG}$. Three levels were differentiated: (i) product, (ii) product class, and (iii) product sector. The numbers in the circles give the percentage contribution of the element to the next higher level.

Energy substitution

Energy substitution was defined as the substitution of the German primary energy mix, mainly produced from fossil fuels by energy from wood incineration as a renewable source of energy. The factor of energetic substitution S_{en} quantified the emission reduction in tonnes carbon per tonnes carbon in fuelwood (t C (t C)$^{-1}$). Energy production through incineration depends mainly on the water content of the wood, so wood with a higher water content can replace less fossil fuel than dry wood. Two cases were distinguished: (i) high water content - fuelwood from thinning and harvesting processes and bark (S_{en1}) and (ii) low water content - residuals of industrial timber processing and wood used at the end of its life cycle (S_{en2}). Based on Burschel et al. (1993) and the carbon emission of primary energy in Germany, S_{en1} was set to 0.363 and S_{en2} to 0.430.

5.2.2 Models

Forest growth model 4C and EFISCEN

The model 4C ('FORESEE' - **FORES**t **E**cosystems in a changing **E**nvironment) was developed to investigate long-term forest behaviour under changing environmental conditions (Bugmann et al. 1997; Schaber et al. 1999; Lasch et al. 2002) at the stand-level. It has been used to study the impact of forest management on diverse forest functions including socio-economic aspects and the wood product chain (Lasch et al. 2005; Fürstenau et al. 2007). The EFISCEN model (**E**uropean **F**orest **I**nformation **SCEN**ario model) is a large-scale matrix model, which uses forest inventory data as input (Pussinen et al. 2001). EFISCEN was developed to project future development of forests (Sallnäs 1990) and has been extended to investigate carbon dynamics in forest biomass, and soils on European, national and regional scale (Nabuurs et al. 2001, 2003; Karjalainen et al. 2002, 2003). Soil carbon is modelled by the soil model YASSO (Liski et al. 2005), which is linked to EFISCEN. From now on we will refer to both these linked models as EFISCEN. 4C and EFISCEN use different approaches for model initialisation, modelling of growth/increment, decomposition, and management. While soil carbon initialisation in 4C is based on measurements, in EFISCEN it is usually based on a spin-up run deriving an equilibrium state of the soil pool. Soil carbon in 4C and EFISCEN is simulated in mineral soil and litter. In addition 4C simulates dead wood, while EFISCEN includes lying dead wood in its soil carbon estimates. Tree growth in 4C is based on physiological functions, while EFISCEN uses data about net annual increment from inventory data. Forest management in 4C is characterised by management plans, which define timing, intensity, and method of thinning, harvesting, and regeneration. Wood demand is the main determinant of resource utilisation in EFISCEN. Management regime is included as minimum and maximum age limits for thinnings and minimum age limits for final fellings. With increasing wood demand, management gets more intensive and rotation lengths are closer to the lower limit defined in the management regimes. Further details on both models are compiled in Appendix C (Table C.1).

Wood product model

The wood product model (WPM) was developed to investigate carbon storage in wood products in use and in landfills. It is based on the model concept of carbon accounting in wood products introduced by Karjalainen et al. (1994) and further developed by Eggers (2002). The parameterisation of the WPM is based on Eggers (2002) and was partly modified according to the current German situation (Fürstenau et al. 2007). The pools of the WPM (products in use and landfill) can be initialised by a spin-up run based on information about the timber production of a previous period. Woody residues from the process of manufacturing wood products are used as biofuel (Figure 5.2). For this study, the WPM was expanded to analyse the reduction of carbon emissions through material substitution of long-lived wood products (in tonnes carbon per hectare and year) based on the factor $S_{mat,C}$. At every time-step in which timber enters a pool of long-lived wood products, regardless of whether it is for the first time or after recycling, it causes a reduction in carbon emissions. In addition, the effect of energy substitution (in tonnes carbon per hectare and year) based on the factors S_{en1} and S_{en2} can be calculated.

5.2.3 Analysis of carbon sequestration in the forest sector and the wood industry sector plus substitution effect

Carbon sequestration in the forest sector was calculated separately for soil and living biomass including above-ground and below-ground biomass. Carbon sequestration in the wood product chain was simulated for wood products and landfills based on the annual amount of harvested timber. Both carbon pools were initialised with a spin-up run over 50 years using timber removal statistics for each study region. Carbon sequestration in all pools was calculated in tonnes of carbon per hectare of forested land and year (t C ha^{-1} a^{-1}). To this end, the final amount of carbon in each carbon pool was subtracted from

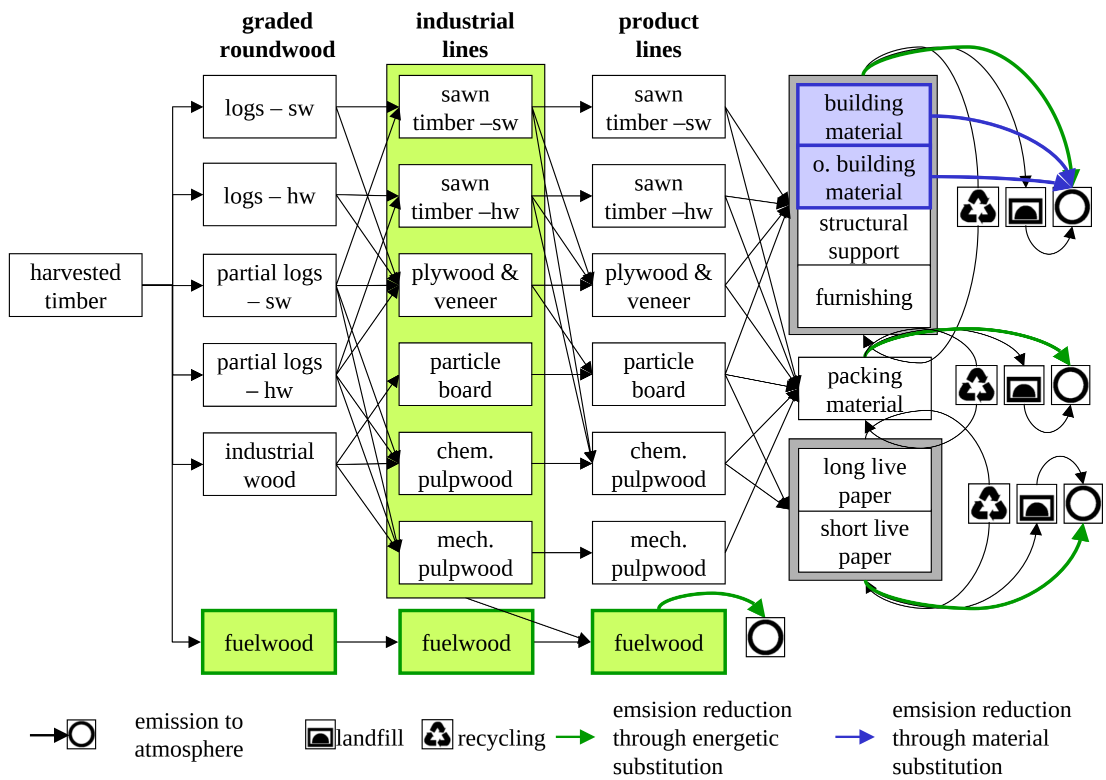


Figure 5.2: Conceptual diagram of the forest wood product model (sw = softwood, hw = hardwood).

the initial amount and the result was divided by the length of the simulation period of 50 years.

The effect of material and energy substitution on carbon emission reduction was also calculated in tonnes of carbon per hectare of forested land and year (t C ha^{-1} a^{-1}). In contrast to the carbon pools, the substitution effects were calculated by adding up the annual carbon emission reduction and dividing it by the simulation time.

Scenario analysis for the wood industry sector

The scenario analysis of the wood industry sector was motivated by uncertainties in the initialisation of the WPM and calculation of $S_{mat,C}$ and possible future changes in the energy mix and ongoing changes in the wood waste management. In the spin-up scenarios S1 and S2, the two extremes of initialising the WPM were tested. While under S1 the WPM was run without initialisation and therefore with empty carbon pools in the wood industry sector, a 1000 year spin-up run was used under S2 with a wood product and landfill carbon pool in equilibrium state. Scenarios D1, D2, I1, and I2 reflected the high variability of $S_{mat,C}$ in wood products through an increase or decrease in $S_{mat,C}$ (Table 5.1). The gradual increase of renewable energy sources in the energy mix was taken into consideration in scenarios E1 and E2. Furthermore, the impact of the EU Council Directive 1999/31/EC (EU (European Union) 1999) on the reduction of biodegradable waste disposal which obliges the reduction of waste from wood processing and abandoned wood products in landfills was studied. In this study a reduction in three stages was assumed: (i) 25% by 2006, (ii) 50% by 2009, and (iii) 65% by 2015 relative to the base scenario. Under L1 it was assumed that all recovered wood waste would be used as fuelwood. Under L2 the recovered wood waste was distributed with 1/3 going to recycling and 2/3 to incineration. In the GHG scenario G1 $S_{mat,C}$ was replaced by $S_{mat,GHG}$. In this way the impact of material substitution on climate protection included additional GHG. In the WPM scenario analysis the impact of the scenarios on carbon sequestration in the wood industry sector plus substitution effects relative to the base scenario (BS) were analysed.

Table 5.1: Carbon emission reduction coefficient of material substitution ($S_{mat,C}$) of the wood industry sector scenarios.

Scenario	Short description	$S_{mat,C}$
BS	Base scenario	0.714
S1	WPM runs without spin-up	BS
S2	WPM runs with spin-up over 1000 years	BS
I1	Increase of $S_{mat,C}$ (+20%)	0.857
I2	Increase of $S_{mat,C}$ (+40%)	1.000
D1	Decrease of $S_{mat,C}$ (-20%)	0.571
D2	Decrease of $S_{mat,C}$ (-40%)	0.428
E1	Dynamic increase of the share of renewable energy in the energy mix up to 20%	0.678[1]
E2	Dynamic increase of the share of renewable energy in the energy mix up to 40%	0.635[1]
L1	Dynamic application of EU directive. All recovered wooden waste is incinerated for energy production	BS
L2	Application of EU directive 2/3 of recovered wooden waste is incinerated for energy production and 1/3 is recycled	BS
G1	$S_{mat,C}$ is replaced by $S_{mat,GHG}$	0.897

[1]Dynamic decrease of $S_{mat,C}$ from 0.714 to given value.

5.2.4 Study area and simulation characteristic

Management unit level - Kleinsee study

The study, at the management unit level, was based on forest conditions in the Kleinsee management unit in the southeast of the federal state of Brandenburg, Germany, which is dominated by Scots pine (*Pinus sylvestris* L.) and oak (*Quercus robur* L. and *Quercus petraea* Liebl.). Forest growth of 43 representatives stands of the Kleinsee management unit were modelled using the forest growth model 4C and the results were extrapolated on management the unit level (Fürstenau et al. 2007). Four management strategies were analysed, including a conservation option that excludes any active management intervention (KL1). The other three management strategies were defined to reflect previous (KL2), current (KL3), and possible future management strategies (KL4). KL2 is oriented towards the production of saw timber in rotation periods of 120 years for pine and 160 years for oak. KL3 fosters regeneration of oak and longer rotation times for all species, while KL4 aims at production of small dimension timber (e.g. for energy production) in shortened rotation periods (Appendix C; Table C.2). Carbon sequestration in the forestry sector was calculated over a 50-year period using a current climate scenario.

Federal and national level - Brandenburg and German study

Simulations at the national level and also for the federal state of Brandenburg were conducted with the forest model EFISCEN. Due to the different applications of management in 4C and EFISCEN, management strategies were defined differently at the federal and national level than in Kleinsee. Actual management was reflected by BB1 for Brandenburg and GR1 in the whole of Germany. Carbon sequestration in the forestry sector was calculated from 2005 to 2055 using a current climate scenario. The total length of the EFISCEN forest resource development projections was 65 years, because EFISCEN's inventory data represent the forest structure of 1990. The extent of removal of wood between 1990 and 2003 was derived from the FAOSTAT database (FAOSTATdata 2005), and used as demand for wood. From 2005 onwards, demand for wood developed according to B2 scenario projections by the Image Team (2001). Under BB2 and GR2, annual wood removal increased by 5 million m^3 at the national level for Scots pine and Norway spruce above the current baseline demand after 2005. This scenario reflected the additional harvest of part of the currently uncut annual increment in Scots pine and Norway spruce stands. It was assumed that 33% of the timber originated from thinnings and 67% from final harvest. A simulation of a no-management was not possible with the EFISCEN model. General characteristics for the three study areas are given in Table 5.2.

Table 5.2: Forest area, tree species composition, and carbon stocks in biomass and soil at the start of the simulation in the three study regions.

	Compartment	Germany	Brandenburg	Kleinsee
Forest area (1000 ha)		9905[1]	957	0.96
Species composition (%)	Spruce	32.6	2.0	0.7
	Pine	27.4	80.9	63.0
	Other coniferous species	5.7	2.0	4.0
	Beech	14.1	2.2	0.5
	Oak	8.8	4.2	30.7
	Other deciduous species	11.4	8.7	1.1
Carbon stock (t C ha^{-1})	Biomass	107.3	69.9	92.6
	Soil (including litter)	123.2	96.3	65.0

[1]Area available for wood supply

5.3 Results

5.3.1 Literature review

In the literature, 15 studies were identified that could be used to calculate $S_{mat,C}$ and/or $S_{mat,GHG}$ (Appendix C; Table C.3). One study examined products available for use in exterior construction work (gardening and orchard construction materials). All other studies focused on the building sector, investigating whole buildings or parts of buildings such as construction pieces (e.g. beams and windows) and interior work (e.g. floorings). Most studies used Life Cycle Analysis to compare the impact of material substitution. It was noted that the system boundaries and investigated phases of the life cycle differed between the studies. Some studies only focused on the production phase, while others even included demolition and recycling (Appendix C; Table C.3).

In almost all cases, the production and use of wood products led to lower carbon and/or GHG emissions than the production and use of the equivalent product. However, there were some notable exceptions where materials other than wood were preferable in terms of carbon emissions (e.g. trusses composed of reinforced concrete and vineyard trellis system made of PVC). If all options given in a study were compared, $S_{mat,C}$ of single wood products ranged from -9.8 to 27.1. $S_{mat,GHG}$ varied from -8.1 to 22.5. These wide ranges were due to the high variability of substitution effects in the production of windows. If windows were excluded, $S_{mat,C}$ ranged from -0.1 to 2.2 and $S_{mat,GHG}$ from 0.02 to 2.2.

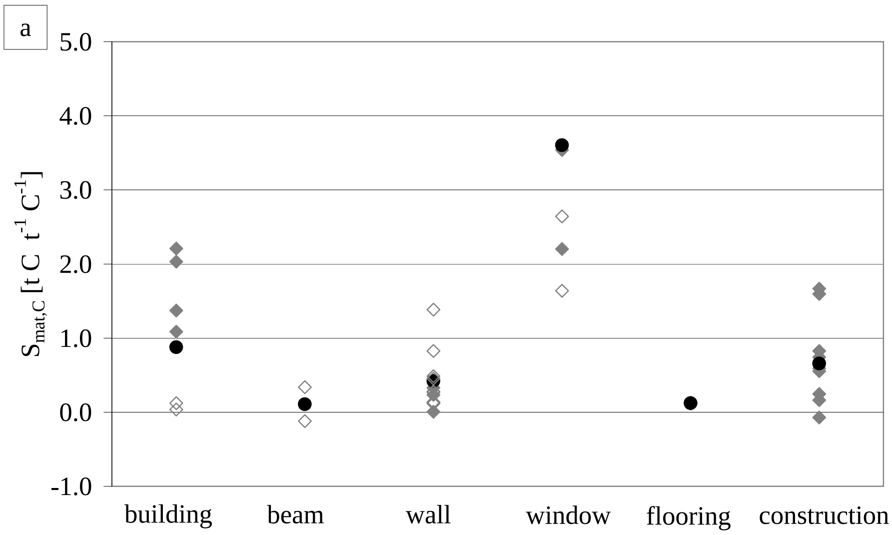
When only the standard or average $S_{mat,C}$ and $S_{mat,GHG}$ values of a wood product calculated on the basis of the individual studies were taken into account (see Section 5.2.1), the range of $S_{mat,C}$ and $S_{mat,GHG}$ became narrower. The mean values of investigated wood products for $S_{mat,C}$ ranged from 0.1 to 3.6 and for $S_{mat,GHG}$ from 0.2 to 3.8 (Figure 5.3a/b). Windows had by far the highest mean value of $S_{mat,C}$ and $S_{mat,GHG}$, followed by the orchard trellis systems. The ranking of the mean values of $S_{mat,C}$ and $S_{mat,GHG}$ differed among the other wood products (Table 5.3).

Table 5.3: Mean $S_{mat,C}$ and $S_{mat,GHG}$ of wood products and wood product classes.

Wood products	$S_{mat,C}$	$S_{mat,GHG}$	Wood product class	$S_{mat,C}$	$S_{mat,GHG}$
Buildings	0.88	0.54	Buildings	0.88	0.54
Windows	3.60	3.81			
Walls	0.42	1.15	Building compartments	0.52	1.10
Beams	0.11	0.59			
Flooring	0.12	0.24			
Swings	0.55	0.70			
Pales	0.16	0.35	Exterior constructions	0.85	1.05
Screens	0.56	0.57			
Vineyard trellis systems	0.76	1.01			
Orchard trellis systems	1.25	1.44			

Due to differences in methodologies applied in the reviewed studies and a lack of detailed information, the following sources of uncertainties in the calculation of $S_{mat,C}$ and $S_{mat,GHG}$ could be distinguished: (i) differences in study design, (ii) uncertainties in converting wood volume or wood mass into carbon content in wood products, (iii) missing information about the mix of primary energy sources (affects only $S_{mat,C}$), (iv) investigation of different sets of GHGs (affects only $S_{mat,GHG}$) and (v) structure of the aggregation scheme of the reviewed studies. A more detailed description on the uncertainties in the calculation of $S_{mat,C}$ and $S_{mat,GHG}$ is given in Table 5.4.

In some instances, the bias in using studies that investigate different phases of the life cycle could be evaluated. Following Baier (1982), the positive impact of material substitution on carbon emission reduction investigating a shed was reduced by approximately 45% if only production was investigated instead of production, use, and demolition phase. In contrast, if only production was investigated for windows (Richter et al. 1996), $S_{mat,C}$ increased.



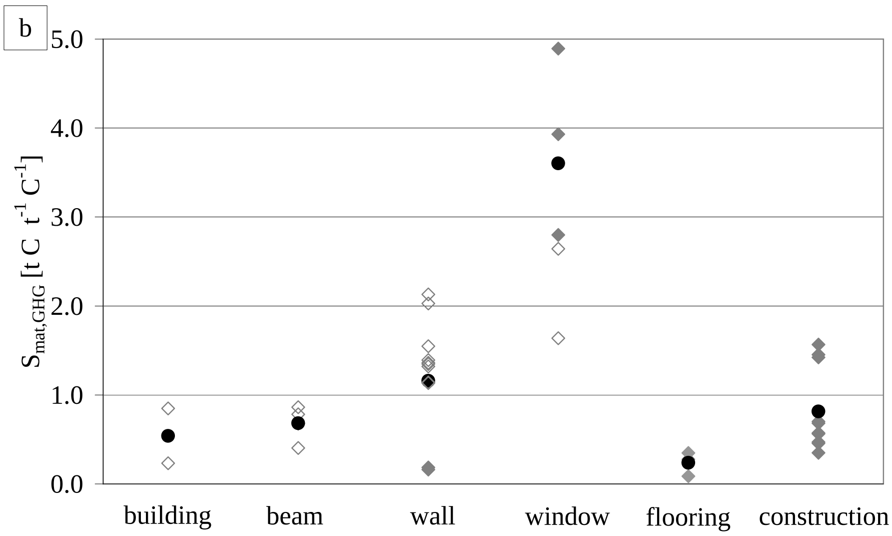


Figure 5.3: $S_{mat,C}$ (a) and $S_{mat,GHG}$ (b) of wood products. If more than one variant of the equivalent product for a wood product was given in a study, only the standard option or mean value of the variants was displayed in the figures. White diamonds mark studies which only examine the production phase and grey diamonds studies which also include other phases of the life cycle. Mean $S_{mat,C}$ (a) and $S_{mat,GHG}$ (b) of the wood products of one group is marked as black dots. Figures 5.3 a/b exclude $S_{mat,C}$ (a) and $S_{mat,GHG}$ (b) of windows that are higher than 5.0.

Table 5.4: Sources of uncertainties in the calculation and comparability of $S_{mat,C}$ and $S_{mat,GHG}$ for single wood products and the $S_{mat,C}$ and $S_{mat,GHG}$ for the wood industry sector buildings.

Source of uncertainty	Description of uncertainty	Impact on $S_{mat,C}$/ $S_{mat,GHG}$
- Study design		
Phase of life cycle in the LCA	Some studies only analysed the manufacture phase of wood products, while others investigated the whole life cycle, including manufacture, use, and demolition.	+/-
System boundaries	System boundaries were defined differently.	+/-
- Carbon content in wood products		
Conversion of wood volume to carbon content	The conversion factor of volume to dry weight and subsequently carbon content in wood products is influenced by wood species and water content. But information about wood species and water content were often not available.	+[1]/-[2]
Conversion of wood mass to carbon content	The applied factor for the conversion of wood mass to carbon content is only valid for dry weight. But in some studies it is not defined if wood mass is given in dry weight or actual wood mass.	+
- Emission from primary energy		
Primary energy consumption	Primary energy was not distinguished in fuels for transportation, energy and heat energy. All three energy sources contain a different mix of fuels and they emit different amounts of carbon.	+/-
Emission of primary energy production of fossil fuels	Emission of the primary energy only contains the direct emission during energy production. Other emissions (e.g. from extraction of resources and transportation) were neglected.	+
- GHG		
GHG	The studies included a different number of GHGs.	+/-
- Aggregation of reviewed studies		
Building sector	Double counting possible as building compartments (seen as own product class) are also accounted in the buildings.	+ / -

[1] Coniferous trees

[2] Deciduous trees

5.3.2 Carbon sequestration in the wood industry sector plus substitution effect

Carbon sequestration in the wood industry sector plus substitution effects ranged from 0.99 to 1.54 t C ha-1 a-1 (Figure 5.4).

Energy substitution accounted for about half of the total carbon sequestration in the wood industry sector plus substitution effects. Landfills were the second largest carbon sink (approximately 26%), followed by carbon emission reduction through material substitution ranging from 14 to 29% of the total carbon sequestration in the wood industry sector plus substitution effects. The lowest amount of carbon was sequestrated in wood products in use, and ranged from 2 to 14%. Differences in the share of carbon sequestration in products in use and in landfills, material substitution, and energy substitution due to management strategies were small within the study regions (Figure 5.4). For detailed results see Appendix C.

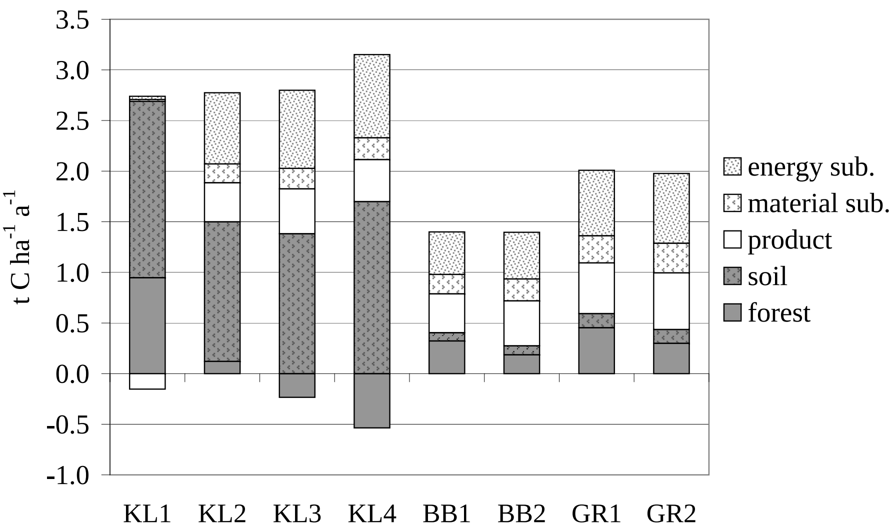


Figure 5.4: Mean annual carbon sequestration in carbon pools of the wood industry sector and carbon emission reduction by substitution in three study areas (KL = Kleinsee, BB = Brandenburg, GR = Germany) under different management scenarios (see Section 5.2.4).

Without management (KL1), the wood industry sector acted as a net carbon source due to carbon reduction in the product pool. The landfill pool acted as carbon sink and, additionally, there was a small positive effect on carbon emission reduction through material and energy substitution due to the initial carbon in the product pool (Figure 5.4). The impact of the WPM scenarios on carbon sequestration plus substitution effects under KL1 was small and is not discussed in Sections 5.4.2.

Uncertainties of carbon sequestration in the wood industry sector plus substitution effects

Uncertainties in the calculation of $S_{mat,C}$ reflected by the WPM scenarios I1, I2, D1, and D2 resulted in a decrease of carbon sequestration in the wood industry sector plus substitution effects relative to the base scenario (BS) by 0.117 (GR2, D2) to 0.037 t C ha^{-1} a^{-1} (KL2, D1) or an increase by 0.037 (KL2, I1) to 0.117 t C ha^{-1} a^{-1} (GR2, I2) under management (Figure 5.5a). Uncertainties due to the chosen initialisation time of the spin-up ranged from -0.401 (KL4, S2) to 0.103 t C ha^{-1} a^{-1} (KL2, KL3, and KL4 under S1) relative to BS, where S1 always resulted in an increase and S2 in a reduction. Carbon sequestration in products was most sensitive to a shortening of running time of the WPM spin-up and therefore to the initial amount of carbon in the pool (Appendix C). A lower initial carbon content led to an increase in the actual carbon sequestration of up to 0.178 t C ha^{-1} a^{-1}. A further increase of the initial carbon pool will only slightly decrease the actual carbon sequestration. The carbon sequestration in the landfill pool decreased under both scenarios; only slightly under S1 but up to 0.382 t C ha^{-1} a^{-1} under S2. Carbon emission reduction by material and energy substitution under S1 was lower relative to BS (up to 6%), while it was slightly increased by about 2% under S2.

Effect of additional WPM scenarios on the carbon sequestration in the wood industry sector plus substitution effects

In comparison to BS, the WPM scenarios G1, E1, E2, L1, and L2 led to a change between -0.242 (KL3, E2) and 0.075 t C ha^{-1} a^{-1} (GR2, G1) in carbon sequestration in the wood industry sector including substitution effects (Figure 5.5b). The assumptions made in the scenario G1 led to a reduction of carbon emission through material substitution by 26% relative to BS. This resulted in an increased carbon sequestration in the wood industry sector plus substitution effects by 3.6 to 4.9% relative to BS or in absolute values by 0.048 (KL3) to 0.075 t C ha^{-1} a^{-1} (GR2).

The other scenarios (E1, E2, L1, and L2) caused a decrease of carbon sequestration plus substitution effects. The ranking of the scenarios was: L2 followed by E1, L1, and L2 (Figure 5.5b). A different ranking was found only in Kleinsee under the short rotation management (KL4) where L2 and E1 switched their rank. Under the energy scenarios the positive effect of material substitution and energy substitution decreased, under E2 up to 29% (BB2). This resulted in a reduction of carbon sequestration in the wood industry sector plus substitution effects relative to BS by -0.150 to -0.242 t C ha^{-1} a^{-1}, which was a decline of about 15%. The decrease in carbon sequestration including substitution effects was half as high under E1, -0.078 to -0.122 t C ha^{-1} a^{-1}.

In contrast to the other scenarios, the landfill scenarios L1 and L2 not only influenced the substitution effects but also the wood product chain (Appendix C). Their main impact was the reduction of the wood waste in landfills. After 50 years, in landfills only 28% (KL2, L1) to 38% (KL4, L2) of the carbon stored under BS was sequestrated. At the same time, the positive impact of energy substitution increased but this effect was only half as strong as carbon reduction in landfills. Furthermore, carbon sequestration in wood products and the emission reduction through material substitution rose slightly under L2. But still, L1 and L2 led to a decrease of the carbon sequestration in the wood industry sector of -0.151 to -0.095 t C ha^{-1} a^{-1} (L1) and -0.113 to -0.071 t C ha^{-1} a^{-1} (L2) relative to the BS.

Under all four WPM scenarios (E1, E2, L1, and L2) the decrease was smallest under the management scenario BB1 followed by BB2. The ranking among the other management scenarios was different under the energy scenarios compared to the landfill scenarios

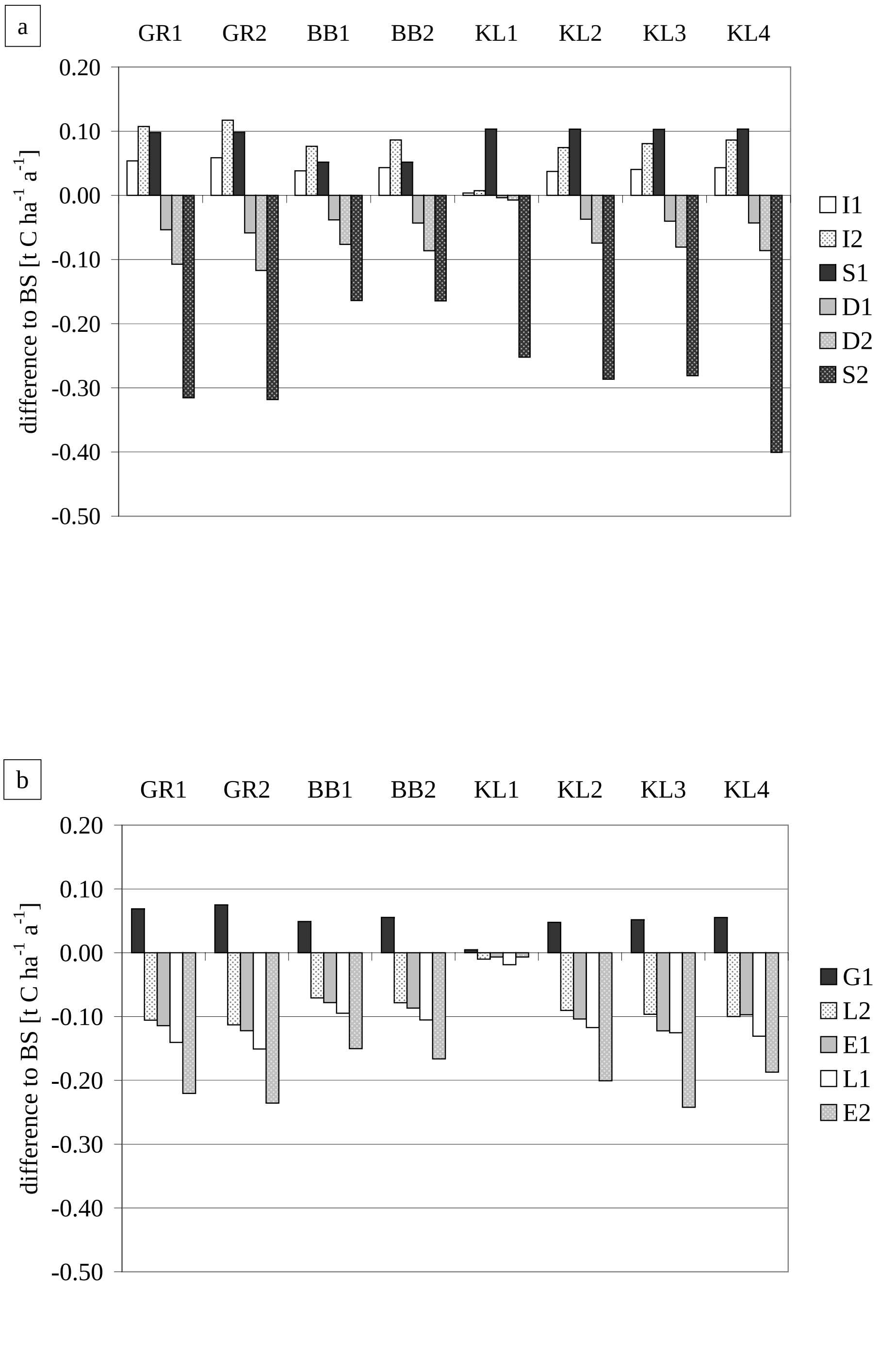


Figure 5.5: Wood industry sector scenario analysis. The figures show the difference of the scenarios (scenario abbreviations as defined in Table 5.1) compared to the base scenario (BS) in t C ha^{-1} a^{-1}. Figure 5.5 (a) shows the impact of uncertainties in the WPM and 5.5 (b) uncertainties due to changing frame conditions in the wood industry sector.

(Figure 5.5b). For detailed results see Appendix C.

5.3.3 Carbon sequestration in the forest sector

The highest amount of carbon was sequestrated within the forest sector when no management was applied for the Kleinsee study area (KL1: 2.69 t C ha^{-1} a^{-1}). Under KL1, two-thirds of the carbon was accumulated in soil and dead wood and one third in living biomass (Figure 5.6). Under management, the highest carbon sequestration was found in Kleinsee under KL2, followed by KL4 and KL3. Soil and dead wood were the main carbon sinks in Kleinsee. The living biomass sequestrated additional carbon only under KL2; the other management scenarios led to a decrease in C stocks in the forest stands.

In comparison, the mean annual carbon accumulation in Brandenburg and Germany ranged from 0.27 to 0.59 t C ha^{-1}. Under all scenarios the living biomass acted as a carbon sink and contributed the main portion to carbon sequestration in the forest sector. Differences in the carbon sequestration in the forest sector between Kleinsee on one hand and Germany and Brandenburg on the other were mainly due to simulated stock changes in the soil and dead wood pools.

5.3.4 Total carbon sequestration in the forest and the wood industry sector plus substitution effects

The mean annual carbon sequestration in the forestry and the wood industry sector plus substitution effects ranged from 1.40 to 2.77 t C ha^{-1}. The lowest carbon sequestration plus substitution effect was found for Brandenburg, followed by Germany and Kleinsee (Table 5.5).

Table 5.5: Carbon sequestration in t C ha^{-1} a^{-1} in the forest and wood industry sector plus substitution effects under the base scenario in all three study regions.

	Forest sector	Product sector			Sum
		Product landfill +	Substitution effects	Sum	
GR1	0.59	0.50	0.91	1.42	2.01
GR2	0.44	0.56	0.98	1.54	1.98
BB1	0.40	0.38	0.61	0.99	1.40
BB2	0.27	0.44	0.68	1.12	1.40
KL1	2.69	-0.15	0.05	-0.10	2.59
KL2	1.50	0.39	0.89	1.27	2.77
KL3	1.15	0.44	0.97	1.42	2.56
KL4	1.16	0.41	1.04	1.45	2.62

In Kleinsee the highest carbon accumulation plus substitution effects was achieved under KL2, while the transient conversion to an oak-dominated forest (KL3) resulted in the lowest carbon sequestration plus substitution effects. Without management (KL1), the annual effect of carbon sequestration plus substitution effects was 2.59 t C ha^{-1}. The ranking of KL1 among the management strategies in Kleinsee in terms of total carbon sequestration plus substitution effects changed under the WPM scenarios. While under I1, I2, and G1 KL1 achieved the lowest total carbon sequestration plus substitution effects,

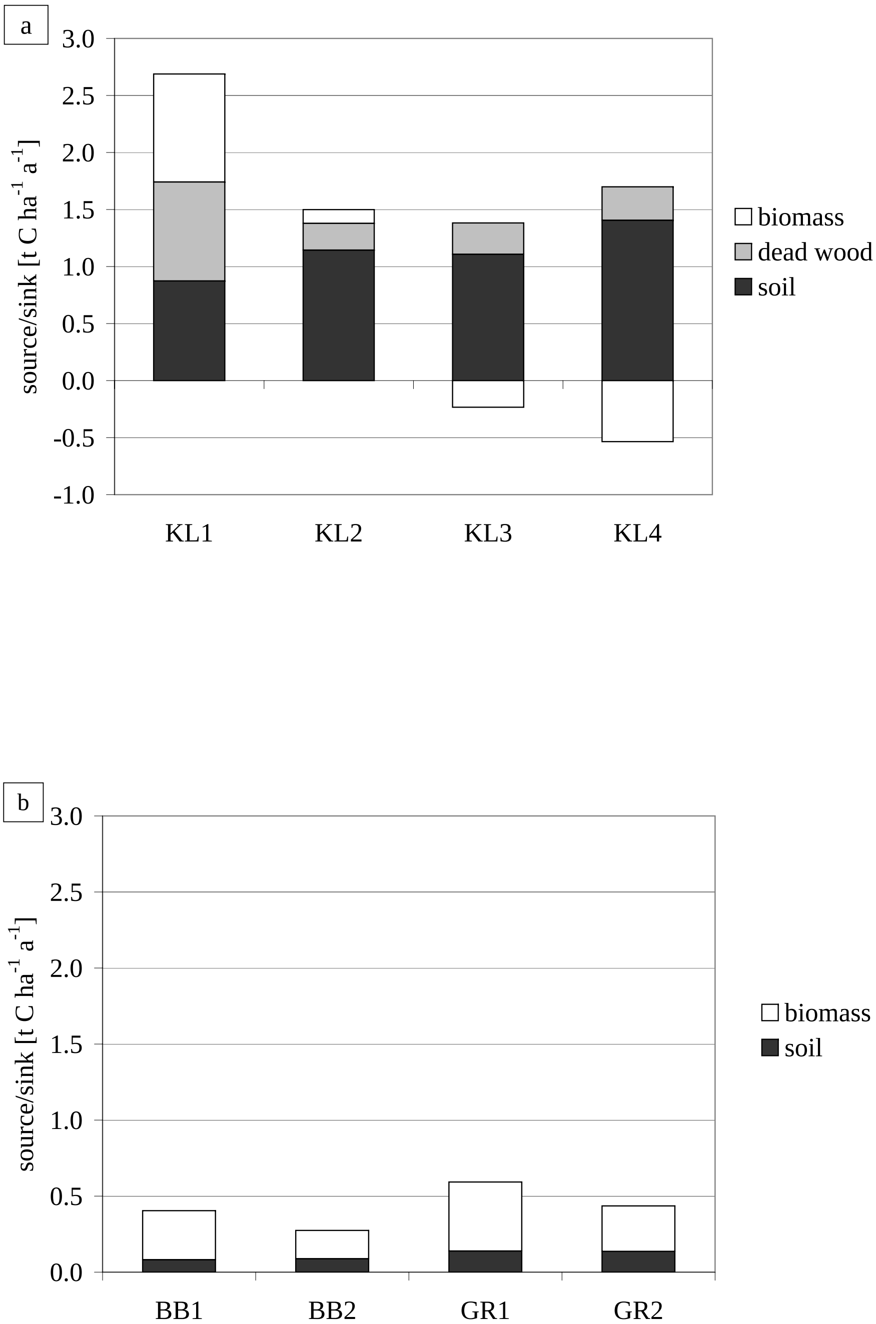


Figure 5.6: Mean annual carbon sequestration in carbon pools of the forest sector (a) Kleinsee, and (b) Brandenburg and Germany (BB and GR) under different management scenarios (see Section 5.2.4).

KL1 exceeded at least one management strategy under the other WPM scenarios; under E2 it exceeded all of them (KL2 to KL4).

Carbon sequestration plus substitution effects in Germany

In Germany the absolute annual carbon sequestration in the forest and the wood industry sector plus substitution effects was 19.9 Mt C under GR1 and 19.6 Mt C under GR2, respectively. Energetic substitution contributed one third to the total carbon sequestration plus substitution effects (Table 5.6). The wood industry sector achieved 70 to 78% of the total carbon sequestration plus substitution effects, 14.02 to 15.27 Mt C a^{-1}.

Table 5.6: Carbon sequestration in Mt C a^{-1} in the forest and the wood industry sector plus substitution effects under the base scenario in Germany.

	Soil	Biomass	Sum	Product	Landfill	Energy sub.	Material sub.	Sum	Total sum
GR1	1.38	4.49	5.87	1.21	3.75	6.41	2.66	14.02	19.9
GR2	1.35	2.96	4.32	1.49	4.06	6.83	2.90	15.27	19.6

5.4 Discussion

5.4.1 Calculation approach of material and energy substitution

The literature review provided sufficient information for the calculation of the parameters $S_{mat,C}$ and $S_{mat,GHG}$ used in our study (see Appendix C; Table C.3). In addition, some of the reviewed studies were in qualitative agreement with the conclusion that wood products were preferable in terms of reducing carbon and/or other GHGs relative to their equivalent products made of other materials. However, these could not be used for our study since the data was not sufficient for our calculation approach (Ritsch 1991; Forintek Canada Corp. 1999; Eyerer and Reinhardt 2000). In contrast, one study by Künniger and Richter (1998) identified an application area (railway sleepers) where the equivalent product emitted less GHGs than the wood product.

Despite a conservative assessment of the carbon emission reduction of material substitution due to deficiencies in the calculation approach (see Table 5.4), $S_{mat,C}$ was found to be an appropriate estimator for long-lived wood products and was within the range of two other studies investigating the substitution effect of wood products on carbon emission. Burschel et al. (1993) first estimated the effect of material substitution of long-lived wood products in Germany. Their calculations resulted in a carbon reduction potential of 0.28 t C m^{-3}, which corresponds to a $S_{mat,C}$ of 1.11. This estimate was higher than ours due to the fact that $S_{mat,C}$ of wood products in newer studies were lower than the ones reported in Burschel et al. (1993). In contrast, Schlamadinger and Marland (1996) reported a substitution factor of 0.50 for long-lived wood products, which was close to our result.

In conclusion, further substitution studies are needed to close the gap for missing products (e.g. furniture, doors, or exterior construction such as bridges) and to give comparable results over the whole life cycle of wood products with the goal to identify areas of wood product use that are most suitable to reduce carbon and other GHG emissions.

When calculating energy substitution it was assumed that energy from fuelwood substituted energy from other sources in proportion to their share in the total energy production within Germany. However this assumption was a simplification and led to a conservative estimate of carbon emission reduction by energy substitution. First, the global energy mix contains fuels used for transportation that cannot readily be substituted by wood. Second, due to power plant and heating system technologies, wood is more likely to replace natural gas and mineral oil than lignite and anthracite in the case of heat production. As for electricity, wood will more readily replace lignite and anthracite than other energy sources (Fritsche et al. 2004; BMU (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit) 2006). If these effects were taken into consideration, the carbon emission reduction by energy substitution will further increase by approximately 10%.

5.4.2 Carbon sequestration in the wood industry sector plus substitution effects

Even with conservative assumptions, the wood industry sector continuously offered a great possibility to sequestrate carbon in wood products and landfills and to reduce carbon emissions by energy and material substitution. Carbon storage potential of the wood product pool was small since the compartment of short- and medium-lived wood products were already in, or close to, an equilibrium state in the BS and after this point additional carbon can only be sequestrated through an increased reuse of wood products (Sathre and Gustavsson 2006), a longer residence time of wood products, or increased timber input. In contrast, the landfill carbon pool was far from an equilibrium state and would be a continuous carbon sink for a long time under actual conditions. Initialising the landfill pool it was assumed that wood products at their end of life were mainly incinerated for heat production in local homes and not landfilled until the first years after World War II as wood was a cheap heating material. To reach equilibrium the landfill pool needed more than 1000 years. Therefore, we chose not to use an initialisation of the landfill pool that is in steady state equilibrium with the current practices.

Major influences on carbon sequestration, primarily in landfills, and substitution effects may be expected from the action of different interdependent factors in the wood industry sector or those related to this sector. So, it could be shown that the law about the disposal of wooden waste (EU (European Union) 1999; BMJ (Bundesministerium für Justiz) 2002) will lead to the intended considerable reduction of carbon sequestration in landfills which over the next 50 years will not be completely compensated by an increased material and energy substitution and higher carbon sequestration in wood products. In addition, the reduction in landfill carbon pools is a temporary effect while the enhanced substitution occurs continually. Furthermore, the energy market was and will in the future be subject to continual change (AGEB (Arbeitsgemeinschaft Energiebilanzen e.V.) 2003). The diminishing resources of fossil fuels, subsidies of green energy, and governmental rules and regulations will force an increase in renewable energy which will decrease the carbon emission reduction potential through energy and material substitution. A lower positive effect on carbon emission reduction through substitution, due to higher shares of energy sources with low carbon emissions during their lifecycle (renewable and nuclear energy) in the energy mix, is already a reality in many European countries (BMU (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit) 2006). The greatest uncertainties about the impact of material substitution were for $S_{mat,C}$, which again emphasises the need for further research on the effect of material substitution. Besides the investigated factors influencing carbon sequestration and carbon emission reduction, Gustavsson et al. (2006) listed additional factors influencing substitution such as infrastructure, quality and quantity of wood, development of new wood products, and improved bioenergy technologies.

These economic and socio-economic factors modulating the magnitude of the substitution effect make up a scenario space of future development that largely depends on future technological and economic decisions. Even if most scenarios suggest a decrease of carbon sequestration and substitution effects in the wood product sector in the coming decades, they will be important for climate protection options.

Another point of interest was the evaluation of sequestration and reduction potential of carbon and other important GHGs in the wood industry sector. Our study showed an increased reduction of CO_2 equivalents by material substitution under the GHG scenario relative to BS. Other studies (Schwaiger and Schlamadinger 1998; Dones et al. 2003) support the assumption that the positive effect of energy substitution will also increase if additional GHGs are considered, due to the fact that fossil fuels (especially anthracite) emit considerable amounts of methane relative to fuelwood during energy production. The strongest effect can be expected on the landfill pool which will act as a GHG source if methane emissions are considered in addition to carbon sequestration (Kohlmaier et al. 2007). But GHG emissions will decrease as consequence of a changed waste management resulting in the positive impact of waste reduction in landfills on climate protection which is in contrast to the findings if only carbon sequestration is considered. Further studies are needed to draw more firm conclusions on the overall effect of GHGs sequestration plus substitution effects in the wood product sector.

5.4.3 Carbon sequestration in the forest sector

In all the three study regions and under all management strategies the forest sector acted as a carbon sink. The magnitude of the predicted carbon sink showed variations, especially in the soil pool, between Kleinsee on one side and Brandenburg and Germany on the other side (Figure 5.6). These differences were due to different approaches for model initialisation, modelling of growth, decomposition, and management. In the EFISCEN projections it was assumed that the soil pool was in equilibrium at the beginning of the simulation. We know that forest soils in Kleinsee, Brandenburg, and most of Germany are not yet in a steady state because of historical management practices and forest depletions, e.g. litter raking until the mid-20th century and monoculture forestry. Therefore, the EFISCEN results may underestimate the carbon sequestration effect in forest soils while 4C was found to project the highest sequestration potential compared to three other models (Thürig et al. 2007). Carbon sequestration in biomass will further increase at a large scale as long as the cuttings will not drastically increase since the actual cuttings are lower than the annual increment. But at smaller scales forest biomass may act as carbon sink or source depending on the management. Carbon sequestration in the Brandenburg case study may be slightly over- or underestimated due to uncertainties in the wood demand in EFISCEN at federal state level (Thürig and Schelhaas 2006). Using 4C the sequestration trend may be slightly overestimated especially in unmanaged forests because the model tends to overestimate growth rates for old trees (Lasch et al. 2005) because biotic and abiotic disturbances (e.g. diseases, storms and wild-fires) that lead to mass losses and growth reduction are not accounted for.

5.4.4 Impact of management on carbon sequestration and substitution effects

Including forestry and the wood industry sectors plus substitution effects in the evaluation of carbon sequestration and carbon emission reduction proved that the abandonment of forest management to sequestrate carbon is not the best option in terms of carbon balance, as also reported by Sathre and Gustavsson (2006). Non-managed forests exceed managed forests in terms of carbon storage in living and dead biomass, at least in the growing and maturing phase of the forest. However, the multiple options within the wood industry sector to reduce carbon emission by carbon sequestration in wood products and the reduction of fossil fuel emissions by material and energy substitution, compensated for the lower net accumulation in the forest and could surpass the possibilities of non-managed forests. In addition, the reduction in carbon emissions from fossil fuels due to energy substitution (which exceeded all other options to sequestrate carbon or reduce carbon emission in the forest and the wood industry sector) and material substitution did not represent a saturating sink as does carbon sequestration in non-managed forests. Instead, it permanently kept up with every consecutive harvest along with the carbon stocks in the forest. Additionally, the abandonment of management in forest ecosystems led to a reduction of carbon stored in the wood products sector thus creating a net source related to oxidation of older products that were not replaced by new products.

The evaluation of different forest management strategies led to the same conclusion: a combined consideration of forest and the wood industry sectors in Kleinsee showed different rankings of management strategies concerning carbon sequestration plus substitution effects than the sole consideration of carbon sequestration without substitution effects (Fürstenau et al. 2007). The studies in Brandenburg and Germany showed that increased forest harvest, and thereby a reduction in the forest biomass carbon pool compared to business as usual, can most likely be offset by the forest sector. It has to be kept in mind when evaluating the carbon sequestration potential plus substitution effects that we aimed at evaluating transient effects starting from a forest with a given species and age class distribution. Variations induced by another status quo may add uncertainties to the evaluation of the different scenarios. A normal age class distribution (e.g. an artificial forest) would have to be assessed in order to evaluate the effect of management strategies on carbon sequestration plus substitution effects in general, independently of transient effects set by the history of previous forest use. However, the scope of this study was to show the effects that may occur within the study regions in the near future. An additional necessary level of evaluation that may change the ranking of the management and WPM scenarios would include GHGs other than CO_2 within forests and landfills. The question is whether methane emissions from landfills will be compensated by GHG reductions within forests or shift the balance in favour of non-managed forests.

5.4.5 Perspective of total carbon sequestration plus substitution effects at national level

A comparable analysis of the carbon sequestration potential of forestry and the wood industry including substitution effects for Germany was not found in the literature. However, single aspects were investigated by Burschel et al. (1993), Baritz et al. (1999), Dieter and Elsasser (2002), Eggers (2002), Janssens et al. (2005), and Kohlmaier et al. (2007). In most cases, their findings were in line with the ones in this study. Concerning the initial carbon stock, differences were found for the wood products pool. Estimates by Burschel et al. (1993), Eggers (2002), and Kohlmaier et al. (2007) were higher (128.0 to 135.7 Mt C) than our result (105.8 Mt C). Higher results by Eggers (2002) and Kohlmaier et al. (2007) were most likely due to the longer initialisation time (60 and 100 years) than used in our study. The initial soil carbon stock was 1220 Mt C and thus was similar to the 1168 Mt C estimated by Baritz et al. (1999) and lower than the 1566 Mt C reported by Burschel et al. (1993). Considering future carbon sequestration and carbon emission reduction, the highest uncertainties were found with respect to carbon sequestration in landfills due to different assumptions concerning waste management and decay rates (Karjalainen et al. 1994; Kohlmaier et al. 2007). The sequestration potential in landfills estimated with our study (3.75 Mt C $a^{-1)}$ was higher than the one estimated with other studies (2.18 Mt C a^{-1}; Eggers 2002 and 2.61 Mt C a^{-1}; Kohlmaier et al. 2007).

With the ratification of the Kyoto Protocol, Germany committed itself to reduce its GHG emissions by 21% in the period between 2008 and 2012 relative to its GHG emissions in the reference year 1990 (340 Mt C; UBA (Umweltbundesamt) 2005). German forests under actual conditions sequestrate 5.87 Mt C a^{-1} in biomass and soils. This represents 8.2% of the GHG emission reduction of 71 Mt C needed to reach the commitment goal. The wood industry sector avoids annual carbon emissions of 14.02 Mt C by sequestration and substitution equivalent to 19.6% of the emission reduction goal if forests are further managed. Increased harvests can additionally enhance the carbon emission reduction by 1.7%, but decrease carbon sequestration in the forest sector by a similar amount. Quantification of scenario effects in the WPM resulted in a decrease up to 2.2 Mt C a^{-1} under the energy scenario E2 (only S2 resulted in a higher decrease) and a maximum increase by 1.1 Mt C under I2 equivalent to -3.1 to 1.5% of Germanys emission reduction goal. Under all scenarios the use of wood for energy production had the highest reduction potential of 9.0%, and therefore the greatest potential to influence the carbon and the GHG balance as also concluded by (Sathre and Gustavsson 2006). Therefore, the use of residues from the wood industry and forest management as biofuel should be increased.

The result of a combined analysis of the forest and the wood industry sectors raises questions concerning the implementation of national climate protection policies that goes beyond the framework of the Kyoto Protocol. Thus policies need to be developed with reference to the whole set of factors determining the overall climate protection effect and not only with reference to single Kyoto Protocol articles. Implementation of incentives that favour increased carbon storage in forests may lead to adverse effects on the whole system if they lead to substitution of wood products by equivalent products. Implementation of incentives that favour the direct use of harvested timber for energy substitution may have a negative effect on the whole system by excluding the exploitation of material substitution in conjunction with energetic substitution. Policies are needed that provide measures to investigate and quantify the best forest management strategy to sequestrate carbon in the forest and the wood industry sector and reduce carbon emissions by substitution effects at national scale.

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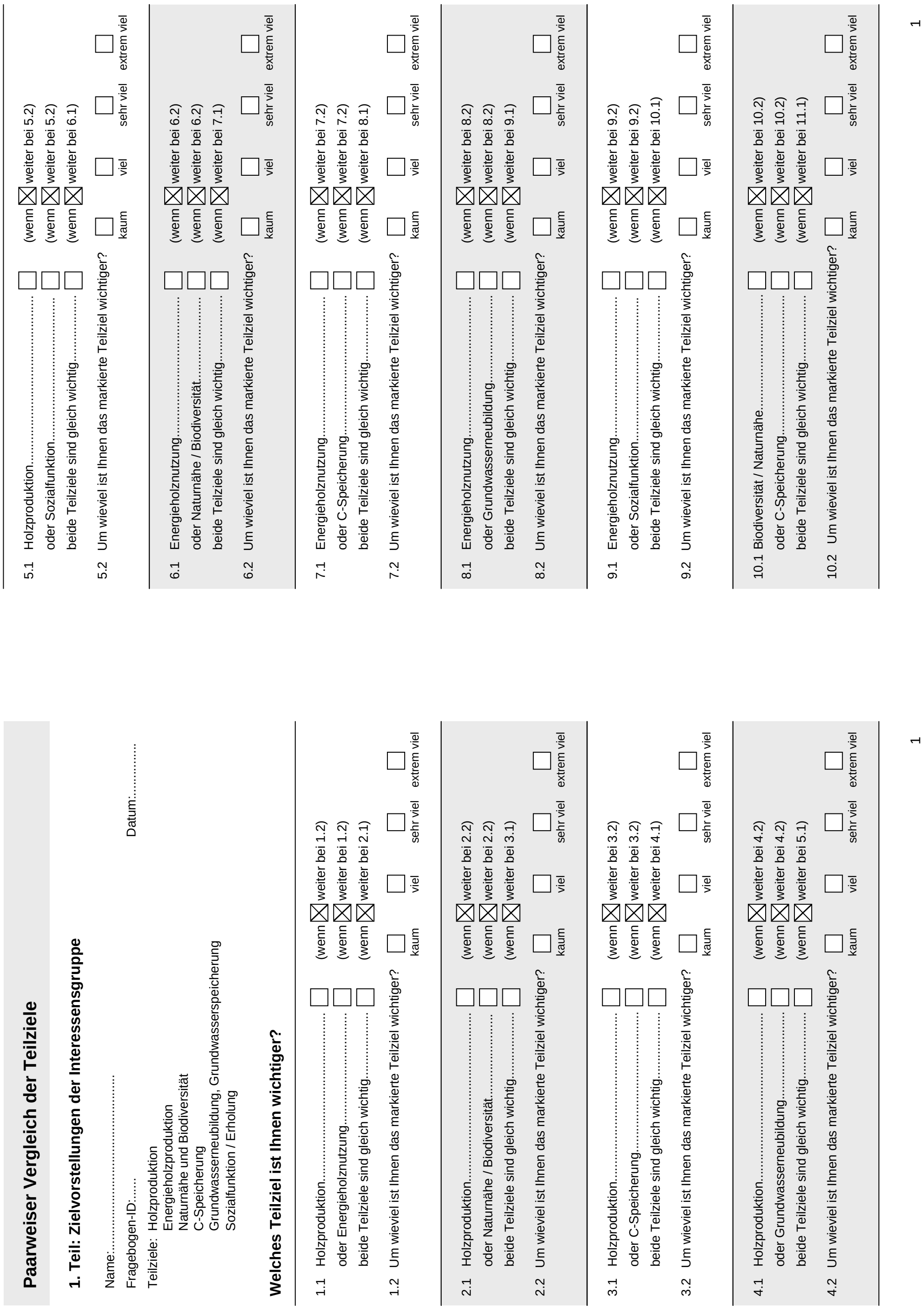
Appendix A

Appendix of Chapter 1



Paarweiser Vergleich der Teilziele

1. Teil: Zielvorstellungen der Interessensgruppe

Name:.......................................

Fragebogen-ID:...... Datum:..............

Teilziele: Holzproduktion
Energieholzproduktion
Naturnähe und Biodiversität
C-Speicherung
Grundwasserneubildung, Grundwasserspeicherung
Sozialfunktion / Erholung

Welches Teilziel ist Ihnen wichtiger?

1.1 Holzproduktion.................. ☐ (wenn ☒ weiter bei 1.2)
oder Energieholznutzung.................. ☐ (wenn ☒ weiter bei 1.2)
beide Teilziele sind gleich wichtig.................. ☐ (wenn ☒ weiter bei 2.1)

1.2 Um wieviel ist Ihnen das markierte Teilziel wichtiger? ☐ kaum ☐ viel ☐ sehr viel ☐ extrem viel

2.1 Holzproduktion.................. ☐ (wenn ☒ weiter bei 2.2)
oder Naturnähe / Biodiversität.................. ☐ (wenn ☒ weiter bei 2.2)
beide Teilziele sind gleich wichtig.................. ☐ (wenn ☒ weiter bei 3.1)

2.2 Um wieviel ist Ihnen das markierte Teilziel wichtiger? ☐ kaum ☐ viel ☐ sehr viel ☐ extrem viel

3.1 Holzproduktion.................. ☐ (wenn ☒ weiter bei 3.2)
oder C-Speicherung.................. ☐ (wenn ☒ weiter bei 3.2)
beide Teilziele sind gleich wichtig.................. ☐ (wenn ☒ weiter bei 4.1)

3.2 Um wieviel ist Ihnen das markierte Teilziel wichtiger? ☐ kaum ☐ viel ☐ sehr viel ☐ extrem viel

4.1 Holzproduktion.................. ☐ (wenn ☒ weiter bei 4.2)
oder Grundwasserneubildung.................. ☐ (wenn ☒ weiter bei 4.2)
beide Teilziele sind gleich wichtig.................. ☐ (wenn ☒ weiter bei 5.1)

4.2 Um wieviel ist Ihnen das markierte Teilziel wichtiger? ☐ kaum ☐ viel ☐ sehr viel ☐ extrem viel

1

5.1 Holzproduktion.................. ☐ (wenn ☒ weiter bei 5.2)
oder Sozialfunktion.................. ☐ (wenn ☒ weiter bei 5.2)
beide Teilziele sind gleich wichtig.................. ☐ (wenn ☒ weiter bei 6.1)

5.2 Um wieviel ist Ihnen das markierte Teilziel wichtiger? ☐ kaum ☐ viel ☐ sehr viel ☐ extrem viel

6.1 Energieholznutzung.................. ☐ (wenn ☒ weiter bei 6.2)
oder Naturnähe / Biodiversität.................. ☐ (wenn ☒ weiter bei 6.2)
beide Teilziele sind gleich wichtig.................. ☐ (wenn ☒ weiter bei 7.1)

6.2 Um wieviel ist Ihnen das markierte Teilziel wichtiger? ☐ kaum ☐ viel ☐ sehr viel ☐ extrem viel

7.1 Energieholznutzung.................. ☐ (wenn ☒ weiter bei 7.2)
oder C-Speicherung.................. ☐ (wenn ☒ weiter bei 7.2)
beide Teilziele sind gleich wichtig.................. ☐ (wenn ☒ weiter bei 8.1)

7.2 Um wieviel ist Ihnen das markierte Teilziel wichtiger? ☐ kaum ☐ viel ☐ sehr viel ☐ extrem viel

8.1 Energieholznutzung.................. ☐ (wenn ☒ weiter bei 8.2)
oder Grundwasserneubildung.................. ☐ (wenn ☒ weiter bei 8.2)
beide Teilziele sind gleich wichtig.................. ☐ (wenn ☒ weiter bei 9.1)

8.2 Um wieviel ist Ihnen das markierte Teilziel wichtiger? ☐ kaum ☐ viel ☐ sehr viel ☐ extrem viel

9.1 Energieholznutzung.................. ☐ (wenn ☒ weiter bei 9.2)
oder Sozialfunktion.................. ☐ (wenn ☒ weiter bei 9.2)
beide Teilziele sind gleich wichtig.................. ☐ (wenn ☒ weiter bei 10.1)

9.2 Um wieviel ist Ihnen das markierte Teilziel wichtiger? ☐ kaum ☐ viel ☐ sehr viel ☐ extrem viel

10.1 Biodiversität / Naturnähe.................. ☐ (wenn ☒ weiter bei 10.2)
oder C-Speicherung.................. ☐ (wenn ☒ weiter bei 10.2)
beide Teilziele sind gleich wichtig.................. ☐ (wenn ☒ weiter bei 11.1)

10.2 Um wieviel ist Ihnen das markierte Teilziel wichtiger? ☐ kaum ☐ viel ☐ sehr viel ☐ extrem viel

1

Figure A.1: Questionnaire used at the stakeholder workshop.

Table A.1: $S_{mat,C}$ and $S_{mat,GHG}$ of single wood products in t C (t C)$^{-1}$. If more than one variant (similar main material) of a wood product and/or its equivalent product existed, the standard option of the wood product and its equivalent product was compared (S) or if no standard option was specified, the mean of the variants was calculated (M). Comparison of wood product and equivalent product in terms of additional ecological factor (POF = photochemical oxidant formation, OD = ozone depletion, HTP = human toxicity potential, STP =soil toxicity potential, ATP = Aquatic toxicity potential).

Product	Reference[1]	Non-wood material	Calculation method	S_C	S_{GHG}	Acidification	Nutrification	POF	OD	HTP	STP	ATP
Single-family house - frame construction	R1	Brick		0.12	0.85	+	+	+				
Single-family house - blockhouse	R1	Brick		0.04	0.23	+	+	+				
Shed (without isolation)	R2	Steel	M	1.09								
		Reinforced concrete		2.03								
Shed (with isolation)	R2	Steel		1.37								
		Reinforced concrete		2.21								
Window	R3	Aluminium	M	2.64	3.63	+						
		PVC		1.64	2.27	-						
Window	R4	Aluminium	S	10.64	4.89	+	o/+	o/+	-	-		+
		PVC		2.20	2.8	+	+	+	-+	-		-+
		Steel		3.54	3.93	+	+	+	-	-+		+
		Stainless steel		15.18	15.87	+	+	+	-	-+		+
		Non-ferrous metal		18.32	19.00	+	+	+	-	-		+
Wall - blockhouse	R3	Vertically perforated brick	M	0.14	1.13	-						
		Brick		0.27	1.36	+						
		Expanded clay - light weight concrete		0.12	1.32	+						
Wall - Holzsystemwand	R3	Vertically perforated brick	M	0.13	1.14	-						
		Brick		0.28	1.39	+						
		Expanded clay - light weight concrete		0.12	1.35	+						

Product	Reference[1]	Non-wood material	Calculation method	S_C	S_{GHG}	Acidification	Nutrification	POF	OD	HTP	STP	ATP
Wall - Ständerwand	R3	Vertically perforated brick	M	0.49	1.55	+						
		Brick		0.83	2.13	+						
		Expanded clay - light weight concrete		0.45	2.03	+						
Wall - conventional wood cladding	R5	Plaster			0.16	+	-	-				
Wall - quality squared wood cladding					0.19							
Wall	R6	Steel		1.38								
Wall	R7	Brick		0.33								
		'Isomodul super'		0.23								
		Brick with insulation		0.01								
Beam - massive glulam	R5[2]	Steel	M		0.54	+						
Beam - truss glulam					0.82							
Truss	R6	Steel		1.205								
Truss	R8	Steel		0.34								
Reinforced				-0.12								
Roof - massive wood	R5	Concrete			0.18	o	-	-				
Roof - light weight construction					0.49							
Ceiling	R9	Reinforced concrete			0.15							
Flooring	R10	PVC		0.11								
		Linoleum		0.13								
Flooring	R1	PVC			0.28	+	-	+				
		Linoleum			0.09	-	-	+				
Flooring	R11	Natural stone			0.35							
Swing	R12	Steel	M	0.55	0.70	+	+	+	-	-	+	-
Pales	R12	Concrete	M	0.16	0.35	+	+	+	+	-	-	-

Product	Reference[1]	Non-wood material	Calculation method	S_C	S_{GHG}	Acidification	Nutrification	POF	OD	HTP	STP	ATP
Screens	R12	Concrete	M	0.25	0.56							
		Brick		0.74	0.68							
		Lime sand brick (solid)		0.66	0.47							
		Lime sand brick (perforated)		0.59	0.57							
Vineyard trellis system	R12	PVC	M	-0.07	0.46	+	+	+	+	-	o/-	-
		Steel		1.60	1.57	+	+	+	-	-	+	-
Orchard trellis system	R12	Concrete	M	1.67	1.42	+	+	+	-	-	o	-
		Steel		0.83	1.45			-	-	+	-	

[1] R1: Scharai-Rad and Welling (2002), R2: Baier (1982), R3: Waltjen et al. (1999), R4: Richter et al. (1996), R5: Petersen2005, R6: Burschel et al. (1993), R7: Richter and Sell (1992), R8: Wegener and Zimmer (2001), R9: Werner et al. (2005), R10: Jönsson et al. (1997), R11: Petersen and Solberg (2003), R12: Künniger and Richter (2001)

[2]Data in Petersen and Solberg 2005 were based on 1 m^3 round wood. It was assumed that this is according to 0.63 m^3 wood in the wood product.

Appendix B

Appendix of Chapter 4

B.1 Equation and paramteters of the utility functions

The following functions were used as utility functions of the decision criteria. They are linear functions defined by supporting points (Table B.1) and are valid between the particular minimum and maximum value of the decision criterion.

$$f_1 = \begin{cases} 0; & x < x_1 \\ b_1 \cdot x + b_2; & x_1 \leq x \leq x_2 \\ 1; & x > x_2 \end{cases} \tag{B.1}$$

$$f_2 = \begin{cases} 0; & x < x_1 \\ b_1 \cdot x + b_2; & x_1 \leq x < x_2 \\ b_3 \cdot x + b_4; & x_2 \leq x < x_3 \\ b_5 \cdot x + b_6; & x_3 \leq x \leq x_4 \\ 1; & x > x_4 \end{cases} \tag{B.2}$$

$$f_3 = \begin{cases} 0; & x < x_1 \\ b_1 \cdot x + b_2; & x_1 \leq x < x_2 \\ b_3 \cdot x + b_4; & x_2 \leq x \leq x_3 \\ 1; & x > x_3 \end{cases} \tag{B.3}$$

$$f_4 = \begin{cases} b_1 \cdot x + b_2; & x < x_1 \\ 1; & x_1 \leq x \leq x_2 \\ b_3 \cdot x + b_4; & x > x_2 \end{cases} \tag{B.4}$$

$$f_5 = \begin{cases} 1; & x < x_1 \\ b_1 \cdot x + b_2; & x_1 \leq x \leq x_2 \\ 0; & x > x_2 \end{cases} \tag{B.5}$$

Table B.1: Parameters of the utility functions of the lowest-level decision criteria (Eqs B.1, B.2, B.3, B.4, B.5; the functions are valid between the minimum and maximum of the decision criterion values achieved at management unit level if any combination of MS can be applied in the study area).

Decision Criterion	Carbon sequestration [t C ha^{-1} a^{-1}]	Percolation [mm]	Dead wood [t C ha^{-1}]	Species distribution [share of pine stands]	Net present value [€ ha^{-1}]	Mean standing stock [m^2 ha^{-1}]	Evenflow of income
Equation	B.1	B.2	B.3	B.4	B.1	B.4	??
b1	0.0052	0.007	0.0.1218	2.5	0.000463	0.007054	-0.01667
b2	-0.5131	0.000	-1.0276	0.0	0.0	-0.5518	1.1667
b3		0.004	0.0070	-2.6316		-0.00272	
b4		0.300	0.6952	2.6316		1.9526	
b5		0.001					
b6		0.750					
x1	121	0	8.21	0.40	0	220	10
x2	282	100	15.0	0.62	2161	350	70
x3		150	43.63				
x4		200					

B.2 Values of the decision criteria

The values of decision criteria (Table B.2) under the chosen 6 management strategies (MS) and three climate scenarios and the achievement values of decision criteria (Table B.3) are described in this Section.

Table B.2: Values of the decision criteria for all management strategies (MS, compare Table 4.3) under three climate scenarios (c = CRU, e = ECHAM4, h = HadCM2).

Decision criterion	Climate scenario	MS 1	2	3	4	5	6
Carbon sequestration [t C ha^{-1} a^{-1}]	c	2.07	1.49	1.24	1.41	1.44	1.37
	e	2.72	1.71	1.46	1.58	1.63	1.56
	h	2.76	1.82	1.58	1.72	1.76	1.67
Percolation [mm]	c	213	194	203	182	190	190
	e	199	183	192	171	178	177
	h	210	195	203	185	190	189
Dead wood [t C ha^{-1}]	c	43.3	11.4	12.4	13.1	10.4	10.1
	e	38.2	11.5	12.6	12.9	10.3	10.0
	h	42.3	11.7	12.9	12.9	10.7	10.4
Share of pine stands [%]	c,e,h	68	68	23	92	83	85
Mean standing stock [m^3 ha^{-1}]	c	480	238	198	161	237	222
	e	717	275	238	187	277	261
	h	610	281	247	191	284	265
Even flow of income [%]	c	-	41	39	19	32	33
	e	-	52	47	35	42	40
	h	-	54	52	37	45	44
Net present value [€ ha^{-1}]	c	-	979	217	289	1421	1418
	e	-	1304	497	743	1810	1840
	h	-	1321	462	811	1834	1874

Table B.3: Utility values of the lowest-level criteria for all management strategies (MS, compare Table 4.3) under three climate scenarios (c = CRU, e = ECHAM4, h = HadCM2).

Partial objective	Decision criterion	Climate scenario	MS					
			1	2	3	4	5	6
Carbon sequestration	Carbon sequestration	c	0.60	0.29	0.16	0.25	0.26	0.22
		e	0.96	0.41	0.27	0.34	0.37	0.33
		h	0.98	0.47	0.34	0.41	0.44	0.39
Ground water recharge	Percolation	c	0.80	0.77	0.77	0.73	0.76	0.77
		e	0.78	0.75	0.77	0.73	0.74	0.74
		h	0.78	0.75	0.77	0.74	0.75	0.74
Biodiversity	Dead wood	c	1.00	0.36	0.49	0.57	0.24	0.21
		e	0.96	0.37	0.51	0.55	0.23	0.19
		h	0.99	0.40	0.54	0.54	0.27	0.24
	Species distriution	c, e, h	0.85	0.85	0.57	0.21	0.44	0.39
Income from timber production	Mean standing stock	c	0.00	1.00	0.84	0.58	1.00	1.00
		e	0.00	1.00	1.00	0.77	1.00	1.00
		h	0.00	1.00	1.00	0.79	1.00	1.00
	Even flow of income	c	0.00	0.48	0.51	0.85	0.64	0.62
		e	0.00	0.30	0.39	0.58	0.47	0.49
		h	0.00	0.27	0.30	0.55	0.42	0.44
	Net present value	c	0.00	0.45	0.08	0.18	0.66	0.66
		e	0.00	0.60	0.21	0.34	0.84	0.85
		h	0.00	0.61	0.19	0.37	0.85	0.87

B.3 Supplentary material

Table B.4: Silvicultural operation costs in € ha^{-1}. Source: price list of a tree nursery, practical experience of forest service personnel and MLUR (Ministerium für Landwirtschaft, Umweltschutz und Raumordnung) (2000) (statistics on tate forestry in Brandenburg)

Silvicultural operation	Costs [€]
Brushing	310
Tending at stand height of 3 m	310
Reforestation pine	3920
Precultivation pine	2740
Reforestation oak	7810
Precultivation oak	5470

Table B.5: Timber prices and harvesting costs of the assortment groups in m^{-3} (over bark). Timber grades are based on the mean diameter (over bark) of the logs: 1b: 15-19 cm, 2a: 20-24 cm, 2b: 25-29 cm, 3a: >30 cm. Source: MLUR (Ministerium für Landwirtschaft, Umweltschutz und Raumordnung) (2000).

Assortment group	Timber grade	Timber price		Harvesting costs	
		Scots pine	Oak spp.	Scots pine	Oak spp.
Partial logs	1b	34.90	-	16.90	-
Partial logs	2a	39.60	37.20	16.30	16.30
Partial logs	2b	41.10	37.20	16.30	16.30
Partial logs	3a	50.10	49.50	15.30	15.30
Industrial roundwood		18.70	17.50	17.40	17.40
Fuelwood		18.70	17.50	17.40	17.40

Table B.6: Distribution of harvested timber from 4C into the product lines of the wood product model.

	Coniferous sawn timber	Non-coniferous sawn timber	Plywood and veneer	Particle board	Chemical pulp	Fuelwood
Coniferous logs	0.97	-	0.03	-	-	-
Non-coniferous logs	-	0.83	0.17	-	-	-
Coniferous partial logs	0.86	-	0.01	-	0.13	-
Non-coniferous partial logs	-	0.53	0.10	-	0.37	-
Industrial wood	-	-	-	0.66	0.34	-
Fuelwood	-	-	-	-	-	1.0

Table B.7: Average carbon sequestration in the soil, dead wood, living biomass and wood product (including landfills) carbon pool in t C ha^{-1} a^{-1} over a simulation time of 100 years under the management strategies (MS, compare Table 4.3) and three climate scenarios (c = CRU, e = ECHAM4, h = HadCM2).

Carbon pools	Climate scenario	MS					
		1	2	3	4	5	6
Soil	c	0.67	1.05	0.84	1.30	1.06	1.04
	e	0.67	1.06	0.82	1.28	1.05	1.04
	h	0.76	1.12	0.91	1.38	1.13	1.11
Dead wood	c	0.85	0.20	0.22	0.22	0.18	0.18
	e	0.75	0.20	0.22	0.21	0.17	0.16
	h	0.90	0.21	0.23	0.22	0.19	0.18
Living trees	c	0.66	-0.09	-0.07	-0.38	-0.13	-0.18
	e	1.41	0.03	0.10	-0.30	-0.01	-0.07
	h	1.21	0.07	0.09	-0.27	0.03	-0.03
Products	c	-0.11	0.32	0.26	0.27	0.33	0.33
	e	-0.11	0.41	0.32	0.39	0.42	0.42
	h	-0.11	0.41	0.36	0.39	0.42	0.42

Table B.8: Partial utilities under the preference setting of a forest manager of public-owned forest for all management programs (MS, compare Table 4.3) under three climate scenarios (c = CRU, e = ECHAM4, h = HadCM2).

Partial objective	Climate scenario	MS					
		1	2	3	4	5	6
Income from timber production	c	0.00	0.42	0.20	0.20	0.50	0.51
Carbon sequestration	c	0.03	0.02	0.01	0.01	0.01	0.01
Ground water recharge	c	0.14	0.13	0.13	0.13	0.13	0.13
Biodiversity	c	0.16	0.10	0.09	0.07	0.06	0.05
Income from timber production	e	0.00	0.46	0.30	0.30	0.54	0.54
Carbon sequestration	e	0.05	0.02	0.02	0.02	0.02	0.02
Ground water recharge	e	0.13	0.13	0.13	0.13	0.13	0.13
Biodiversity	e	0.15	0.10	0.09	0.07	0.06	0.05
Income from timber production	h	0.00	0.46	0.29	0.20	0.54	0.55
Carbon sequestration	h	0.05	0.03	0.02	0.02	0.02	0.02
Ground water recharge	h	0.13	0.13	0.13	0.13	0.13	0.13
Biodiversity	h	0.16	0.11	0.10	0.06	0.06	0.05

Table B.9: Partial utilities under the preference setting of a private forest owner for all management programs (MS, compare Table 4.3) under three climate scenarios (c = CRU, e = ECHAM4, h = HadCM2).

Partial objective	Climate scenario	MS					
		1	2	3	4	5	6
Income from timber production	c	0.00	0.47	0.22	0.22	0.55	0.56
Carbon sequestration	c	0.00	0.47	0.22	0.22	0.55	0.56
Ground water recharge	c	0.03	0.03	0.03	0.03	0.03	0.03
Biodiversity	c	0.16	0.11	0.09	0.07	0.06	0.05
Income from timber production	e	0.00	0.50	0.33	0.33	0.59	0.60
Carbon sequestration	e	0.11	0.05	0.03	0.04	0.04	0.04
Ground water recharge	e	0.03	0.03	0.03	0.03	0.03	0.03
Biodiversity	e	0.16	0.11	0.09	0.07	0.06	0.05
Income from timber production	h	0.00	0.50	0.32	0.36	0.60	0.60
Carbon sequestration	h	0.11	0.05	0.04	0.05	0.05	0.04
Ground water recharge	h	0.03	0.03	0.03	0.03	0.03	0.03
Biodiversity	h	0.16	0.11	0.10	0.07	0.06	0.06

Table B.10: Partial utilities under the preference setting of an environmental organisation for all management programs (MS, compare Table 4.3) under three climate scenarios (c = CRU, e = ECHAM4, h = HadCM2).

Partial objective	Climate scenario	MS					
		1	2	3	4	5	6
Income from timber production	c	0.00	0.17	0.08	0.08	0.21	0.21
Carbon sequestration	c	0.15	0.07	0.04	0.06	0.07	0.06
Ground water recharge	c	0.20	0.19	0.19	0.19	0.19	0.19
Biodiversity	c	0.23	0.15	0.13	0.10	0.08	0.07
Income from timber production	e	0.00	0.19	0.12	0.12	0.22	0.22
Carbon sequestration	e	0.24	0.10	0.07	0.09	0.09	0.08
Ground water recharge	e	0.20	0.19	0.19	0.19	0.19	0.19
Biodiversity	e	0.23	0.15	0.13	0.10	0.08	0.07
Income from timber production	h	0.00	0.19	0.12	0.13	0.22	0.22
Carbon sequestration	h	0.24	0.12	0.09	0.10	0.11	0.10
Ground water recharge	h	0.20	0.19	0.19	0.19	0.19	0.19
Biodiversity	h	0.23	0.16	0.14	0.09	0.09	0.08

Appendix C

Appendix of Chapter 5

Section C.1 gives a tabulated comparison of the models 4C and EFISCEN and the management strategies in Kleinsee. Further more Section C.1 provides general information on the studies used to calculate $S_{mat,C}$ and $S_{mat,GHG}$. Section C.2 gives detailed results of energy and material substitution and carbon sequestration in wood products in use and landfills under the WPM scenarios.

C.1 Model description

Table C.1: Information about the structure and function of the forest models 4C and EFISCEN as applied in the current study. For further details see (Freeman et al. 2005; Pussinen et al. 2001)

	4C	EFISCEN
Spatial resolution	Cohorts and stand	Federal and national level
Model simulation options	Tree species composition Forest structure Leaf area index Ecosystem carbon Water balances Forest management	Forest resource projection Ecosystem carbon Forest management
Tree species	Oaks (*Quercus robur* L., and *Quercus petraea* Liebl.) Norway spruce (*Picea abies* L. Karst.) Scots pine (*Pinus sylvestris* L.)	European beech (*Fagus sylvatica* L.) Oak (*Quercus spp.*) Long-life deciduous species Short-life deciduous species Norway spruce Scots pine Douglas fir (*Pseudotsuga menziesii* (Mirbel) Franco) Fir (*Abies grandis* (Douglas ex D. Don) Lindl.) Larch (*Larix spp.*)
Climate data	Temperature Precipitation Air vapour pressure Solar radiation Wind speed CO2 concentration Nitrogen deposition	Effective temperature sum in the growing season (0°C threshold) Drought index during the growing season (precipitation minus potential evapotranspiration during the growing season)
Management options[1]	Thinning (M, I, T) Harvesting (M, I, T) Regeneration (M, S)	Thinning (I, T, S) Harvesting (I, T, S) Regeneration (S)
Carbon balance	Gross primary production Autotrophic respiration Heterotrophic respiration	Net annual volume increment Turn-over rates Litter fractionation Decomposition
Carbon pools	Biomass (above- and below-ground) Soil, including litter Timber products in use and in landfills Reduced fossil carbon emission through energetic and material substitution	Biomass (above- and below-ground)[2] Soil, including litter Harvested timber (outside the model)

[1] The following option can be chosen by the user: M - method, I - intensity, T - timing, S - tree species

[2] Estimated by converting growing stock volume to total whole-tree biomass (i.e. biomass in stem, branches, foliage, coarse roots and fine roots) using basic wood density and age-dependent biomass expansion factors (Somogyi et al. 2007) and subsequently to whole tree carbon stocks assuming a carbon content of 50%.

Table C.2: Description of management strategies in the Kleinsee case study.

Management scenario	Site fertility index[1]	Tree species (present)	Thinning interval	Thinning intensity	Rotation period length	Harvesting system[2]	Tree species (future)
KL1	All	Pine/oak	-	-	-	-	Pine/oak
KL2	All	Pine/oak	10	0.9	120/160	cc	Pine/oak
KL3	A, Z	Pine	10	0.8	140	cc	Pine
	Z	Oak			180		
	M, K	Pine/oak			140/180	sh	Oak
KL4	A, Z	Pine	7	0.7	100	cc	Pine
	M, K	Pine			80		
	All	Oak			140		

[1] Site fertility index as used in German forest site classification: A - poor, Z - quite poor, M - medium fertile, K - fertile

[2] Harvesting system: cc - clear-cut, sh - shelterwood cut

Table C.3: General information on studies used to calculate $S_{mat,C}$ and $S_{mat,GHG}$.

Product	Original source	Original source quoted by	Equivalent material	Phases of life cycle[1]	C	GHG
Single-family house	BM-BAU (Bundesministerium für Raumordnung, Bauwesen und Städtebau) (1993)	Scharai-Rad and Welling (2002)	Brick	P	x	x
Shed	Baier (1982)		Steel, reinforced concrete	P, U, D	x	
Window	Waltjen et al. (1999)		Aluminium, PVC	P	x	x
Window	Richter et al. (1996)		Aluminium, steel, stainless steel, wood-aluminium, PVC	P, U	x	x
Wall	Waltjen et al. (1999)		Brick, vertically perforated brick, expanded clay - lightweight concrete	P	x	x
Wall	Boyd et al. (1976)	Burschel et al. (1993)	Steel	P	x	
External wall	Jarnehammar (1998)	Petersen and Solberg (2005)	Plaster	P, U		x
Wall	Richter and Sell (1992)		Brick, 'Isomodul-Super', brick with insulation	P, U, D, R	x	x
Beam	Engelbertsson (1997)	Petersen and Solberg (2005)	Steel	P	x	
Truss	Wegener and Zimmer (2001)		Steel, reinforced concrete	P	x	
Roof	Jarnehammar (1998)	Petersen and Solberg (2005)	Concrete	P, U		x
Ceiling	Werner et al. (2005)		Reinforced concrete	P, D		x
Flooring	Jönsson et al. (1997)		PVC, linoleum	P, U, D	x	
Flooring	Jönsson et al. (1997)	Scharai-Rad and Welling (2002)	PVC, linoleum	P, U, W[2]		x
Flooring	Petersen and Solberg (2003)		Natural stone	P, U, W		x
Exterior work	Künniger and Richter (2001)		Steel, PVC, concrete, brick, lime sand brick	P, U, D, W	x	x[3]

[1] P - production included, U - use included, D - demolition included, W - waste management included, R - recycling included, E - emission from production of electricity included

[2] Energy recovery through recycling was included

[3] Demolition and waste management was included

C.2 Results of the WPM

Table C.4: Carbon emission reduction by material substitution in t C ha^{-1} a^{-1} under all WPM scenarios in the three study regions.

	BS	I1	I2	D1	D2	E1	E2	L1	L2	G1	S1	S2
GR1	0.268	0.322	0.376	0.215	0.161	0.240	0.230	BS	0.286	0.337	0.247	0.278
GR2	0.293	0.351	0.410	0.234	0.176	0.262	0.251	BS	0.311	0.368	0.272	0.302
BB1	0.191	0.229	0.267	0.153	0.115	0.170	0.163	BS	0.202	0.240	0.180	0.196
BB2	0.216	0.259	0.302	0.173	0.129	0.192	0.184	BS	0.228	0.271	0.204	0.221
KL01	0.018	0.022	0.026	0.015	0.011	0.016	0.016	BS	0.024	0.023	0.000	0.024
KL02	0.186	0.223	0.260	0.149	0.112	0.169	0.163	BS	0.200	0.234	0.168	0.195
KL03	0.202	0.242	0.282	0.161	0.121	0.178	0.168	BS	0.215	0.253	0.183	0.210
KL04	0.215	0.258	0.302	0.172	0.129	0.203	0.198	BS	0.231	0.271	0.197	0.224

Table C.5: Carbon emission reduction by energy substitution in t C ha^{-1} a^{-1} under all WPM scenarios in the three study regions.

	BS	I1	I2	D1	D2	E1	E2	L1	L2	G1	S1	S2
GR1	0.647	BS	BS	BS	BS	0.561	0.464	0.771	0.757	BS	0.614	0.654
GR2	0.689	BS	BS	BS	BS	0.598	0.495	0.822	0.807	BS	0.657	0.697
BB1	0.421	BS	BS	BS	BS	0.363	0.298	0.504	0.494	BS	0.403	0.425
BB2	0.461	BS	BS	BS	BS	0.398	0.327	0.553	0.543	BS	0.444	0.465
KL1	0.032	BS	BS	BS	BS	0.028	0.028	0.052	0.050	BS	0.000	0.033
KL2	0.703	BS	BS	BS	BS	0.616	0.525	0.810	0.799	BS	0.670	0.709
KL3	0.772	BS	BS	BS	BS	0.674	0.564	0.885	0.872	BS	0.740	0.779
KL4	0.822	BS	BS	BS	BS	0.737	0.652	0.943	0.930	BS	0.790	0.828

Table C.6: Carbon sequestration in wood products in use in t C ha^{-1} a^{-1} under all WPM scenarios in the three study regions.

	BS	I1	I2	D1	D2	E1	E2	L1	L2	G1	S1	S2
GR1	0.122	BS	BS	BS	BS	BS	BS	BS	0.138	BS	0.300	0.084
GR2	0.150	BS	BS	BS	BS	BS	BS	BS	0.168	BS	0.328	0.112
BB1	0.125	BS	BS	BS	BS	BS	BS	BS	0.137	BS	0.220	0.105
BB2	0.155	BS	BS	BS	BS	BS	BS	BS	0.169	BS	0.250	0.135
KL1	-0.173	BS	BS	BS	BS	BS	BS	BS	-0.170	BS	0.000	-0.206
KL2	0.075	BS	BS	BS	BS	BS	BS	BS	0.085	BS	0.248	0.042
KL3	0.107	BS	BS	BS	BS	BS	BS	BS	0.121	BS	0.280	0.074
KL4	0.033	BS	BS	BS	BS	BS	BS	BS	0.045	BS	0.206	0.000

Table C.7: Carbon sequestration in wood products on landfills in t C ha^{-1} a^{-1} under all WPM scenarios in the three study regions.

	BS	I1	I2	D1	D2	E1	E2	L1	L2	G1	S1	S2
GR1	0.378	BS	BS	BS	BS	BS	BS	0.114	0.130	BS	0.353	0.084
GR2	0.409	BS	BS	BS	BS	BS	BS	0.125	0.142	BS	0.384	0.112
BB1	0.259	BS	BS	BS	BS	BS	BS	0.081	0.092	BS	0.245	0.105
BB2	0.290	BS	BS	BS	BS	BS	BS	0.092	0.104	BS	0.275	0.135
KL1	0.019	BS	BS	BS	BS	BS	BS	-0.019	-0.017	BS	0.000	-0.206
KL2	0.310	BS	BS	BS	BS	BS	BS	0.086	0.100	BS	0.291	0.042
KL3	0.336	BS	BS	BS	BS	BS	BS	0.098	0.112	BS	0.317	0.074
KL4	0.382	BS	BS	BS	BS	BS	BS	0.130	0.146	BS	0.363	0.000

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