separate reports, which are cited in the references. Special thanks are due to our colleagues Dr. Peter Schwarzbauer from the University of Agricultural Sciences in Vienna, who gave direction to the development of the model with his good advice, and Dr. H. Englert of the Federal Research Centre for Forestry and Forest Products in Hamburg, who calculated data on the potential timber yield in Germany and made these available for this study. As the sources of the data and pieces of information included in the base data for the simulations with the model cannot all be mentioned individually, I wish to thank all providers of information collectively here. Thanks also to Dr. Marcus Lindner and Alison Schlums from the Potsdam Institute for Climate Impact Research and Tessa Feller in Freising for their helpful revision and translation of the manuscript and two anonymous reviewers for their critical comments on the first draft of this paper.

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Integrating Forest Growth Dynamics, Forest Economics and Decision Making to Assess the Sensitivity of the German Forest Sector to Climate Change

Integration von Waldentwicklungsdynamik, Forstökonomie und Entscheidungsverhalten in Forstbetrieben zur Beurteilung der Gefährdung der deutschen Forstwirtschaft durch den Klimawandel

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Summary

The "German Forest Sector under Global Change" study integrated forest succession, growth and yield projections, decision-making in forest management, and forest economics in a modelling framework of coupled simulation models. National forest inventory and regional forest soil data were linked with interpolated climate data to obtain comparable and consistent input data for the simulation models. Based on a stratification of the input data, a forest estate model representing the most important forest types of German forests was developed. The forest stand simulator SILVA and the forest scenario model ActioSilva were linked to the forest estate model to project stand growth under different management strategies 30 years into the future, using the current climate and a climate change scenario for the second half of the 21st century. The process-based forest model 4C was applied to investigate changes in forest productivity and the forest product market model FPMM calculated implications of the changes in forest growth for the timber market and the wood industry. This paper describes the conceptual approach for the integrated assessment, presents key results and discusses the achievements and limitations of the study. The results indicate that impacts of climate change in Germany will be site- and species-specific. Negative growth changes are likely to occur on sites where drought stress increases under climate change. Where precipitation is not the limiting growth factor, however, forest productivity may also increase. Different assessment methods produced sometimes contrasting results, which points to the need for further testing and improvement of the applied methodology. The comparison of two climate change scenarios with different precipitation trends shows that the projected impacts of climate change on the German forest sector are very sensitive to the amount and annual distribution of precipitation in the future climate. According to the forest product market model, potential timber production in Germany increased in the baseline projection under current climate. Compared to this baseline, climate change resulted in a further increase of timber production by 5 % in the wet climate change scenario and a decrease of 9 % in the dry scenario. We conclude that climate change constitutes a manageable risk to the German forest sector. However, especially under unfavourable site conditions significant negative ecological and socio-economic impacts are possible. The paper concludes with an outlook on further research needs.

Keywords: climate change, forest sector, inter-disciplinary impact assessment, integrated assessment

Zusammenfassung

Die Studie „Wälder und Forstwirtschaft Deutschlands im globalen Wandel" integrierte Auswirkungen von Klimaänderungen auf Waldentwicklungsdynamik, Waldwachstum, Entscheidungsverhalten bei der Waldbewirtschaftung und forstökonomische Konsequenzen in einer modellgestützten Wirkungsanalyse. Inventurdaten aus der Bundeswaldinventur und dem Datenspeicher Waldfonds wurden mit Standortsinformationen der Bundesländer und interpolierten Klimadaten verknüpft, um einheitliche und methodisch konsistente Eingangsdaten für die Simulationsmodelle zu generieren. Ausgehend von einer Strati-

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fizierung der Waldinventur- und Standortsdaten wurde ein Modellbetrieb bestehend aus den wichtigsten
Waldbestandestypen Deutschlands gebildet. Der Wachstumssimulator SILVA und der Forstbetriebssi-
mulator ActioSilva wurden genutzt, um die Bestände des Modellbetriebs mit unterschiedlichen Bewirt-
schaftungsstrategien unter heutigen und veränderten Klimabedingungen über 30 Jahre zu simulieren.
Mit dem prozessbasierten Modell 4C wurden Produktivitätsveränderungen unter verändertem Klima
untersucht und mit dem Holzmarktmodell FPMM die Konsequenzen des veränderten Wachstums für
den Holzmarkt und die Holzindustrie analysiert. Der methodische Ansatz der integrierten Wirkungsana-
lyse sowie ausgewählte Ergebnisse der Teilprojekte werden dargestellt und die Einsatzmöglichkeiten
und Grenzen der Simulationsmodelle diskutiert. Die Resultate weisen auf unterschiedliche Auswirkun-
gen der Klimaänderung in Abhängigkeit von Standort und Baumart hin. Wachtumsreduktionen sind
wahrscheinlich auf Standorten mit zunehmendem Wasserstress. Bei ausreichender Wasserversorgung
sind dagegen auch Produktivitätssteigerungen möglich. Unterschiedliche Modellansätze zeigten teilweise
abweichende Resultate, daher ist eine weitergehende Validierung und Verbesserungen der angewendeten
Methoden sinnvoll. Der Vergleich zweier Klimaänderungsszenarien mit gegensätzlichen Niederschlags-
trends unterstreicht, dass die simulierten Auswirkungen von Klimaänderungen in der deutschen Forst-
wirtschaft sehr sensibel auf die Höhe und die jahreszeitliche Verteilung der Niederschläge im künftigen
Klima reagieren. Das Holzmarktmodell simulierte in einem Basisszenario mit heutigem Klima einen
Anstieg der Holzproduktion in Deutschland. Im Vergleich hierzu führten die Klimaänderungen zu
einem weiteren Anstieg der Holzproduktion um 5 % im feuchten Klimaänderungsszenario und zu einer
Reduktion um 9 % im trockeneren Szenario. Wir folgern, dass die Auswirkungen der Klimaänderungen
von der deutschen Forstwirtschaft generell zu bewältigen sind. Besonders unter ungünstigen Standorts-
verhältnissen sind allerdings auch gravierendere ökologische und sozioökonomische Konsequenzen
möglich. Basierend auf den Erfahrungen der Studie werden Empfehlungen für weitergehende For-
schungsaktivitäten im Bereich Waldwirtschaft und globale Klimaänderungen gegeben.

Schlüsselwörter: Klimaänderung, Forstwirtschaft, interdisziplinäre Simulationsstudie, integrierte Bewertung

1 Introduction

Anthropogenic climate change will not only affect ecosystem processes such as carbon exchange and disturbance regimes, it is also likely to influence the economics of forest management and resource utilization. A comprehensive assessment of climate change impacts on forests and the forest sector thus needs to consider different aspects and their associated scientific disciplines, including tree physiology, genetics, forest ecology, growth and yield, silviculture, forest planning, and forest economics. The overall nature of possible climate change impacts was summarised in LINDNER and CRAMER (2002), more detailed reviews can be found in a wide body of literature, such as KIRSCHBAUM et al. (1996) or PUHE and ULRICH (2001). The complexity of interactions between ecosystem processes, forest management, and ecosystem services such as biodiversity, water and soil protection, and recreation is challenging decision-making. This is especially true for forest management in Central Europe where long rotation times of between 80 and more than 200 years are typical. Over the last few years there has been growing interest in providing support for policy making by integrating impact assessments in forest sector impact studies (BINKLEY and VAN KOOTEN 1994, JOYCE 1995, KARJALAINEN et al. 1997, WINNETT 1998, JOYCE and BIRDSEY 2000, JOYCE et al. 2001). A recent review of experiences with integrated forest impact assessment studies (LINDNER et al. 2002) has discussed different ways to integrate cross-disciplinary impact assessments: linking, coupling and integrated modelling. Most of the reviewed studies applied a "one-way" linking where results from one set of models were used as input in a different set of models. More advanced methods like coupling of disciplinary models with feedback between models or integrated modelling, where sub-models are embedded into a common model framework, have not been used in forest impact assessment efforts to date. The German Forest Sector under Global Change (GFS) study attempted an integrated assessment, by using an interdisciplinary network of seven German forest research groups working in a common project framework over a period of three years. This paper synthesizes the results of the study, details being presented elsewhere in this journal supplement (BARTELHEIMER 2002, DÖBBELER and SPELLMANN 2002, ĎURSKÝ 2002, DUSCHL and SUDA 2002, LASCH et al. 2002, LIESEBACH 2002, LINDNER and CRAMER 2002, POTT and FABRIKA 2002, PRETZSCH 2002, PRETZSCH and ĎURSKÝ 2002, SCHLOTT and GUNDERMANN 2002, WOLFF 2002). Here we describe the conceptual approach for the integrated assessment, present key results, and discuss the achievements and limitations of the approach. The paper ends with some general conclusions and research recommendations.

2 Methodological approach

To assess the possible impacts of climatic change on forests and forestry in Germany, different processes need to be considered. In this study, we integrated forest succession, growth and yield projections, decision-making in forest management, and forest economics in a consistent modelling framework of coupled simulation models (Fig. 1). The assessment depends on geo-referenced data of forests and growth-related site factors. The available information from forest inventory data bases at the national and regional level had to be harmonized, because eastern and western Germany used different inventory concepts up until 1990. Also, forest soils data for the locations of the west German national forest inventory existed only in regional data sets that used inconsistent classification schemes (WOLFF 2002). The result of the data processing was the first comparable and consistent set of national forest stand and forest soil data on the basis of systematic grid samples in Germany (Fig. 2). The applied climate data and scenarios were described in detail in LINDNER and CRAMER (2002). The data for the current climate was interpolated to the investigated forest sites based on a dataset of the Climate Research Unit of the University of East Anglia, UK (NEW et al. 1998). Two different climate change projections based on the global circulation models HadCM2 (MITCHELL et al. 1995) and ECHAM4 (ROECKNER et al. 1996) were used in the assessment. Both scenarios project a temperature increase of approximately 3K, but they differ in the amount and regional distribution of precipitation (on average HadCM2 +20 %, ECHAM4 −1 %).

2.1 Simulating forest growth and tree responses to climate change

The GFS study relied as far as possible on the application of already existing data sources and simulation models.

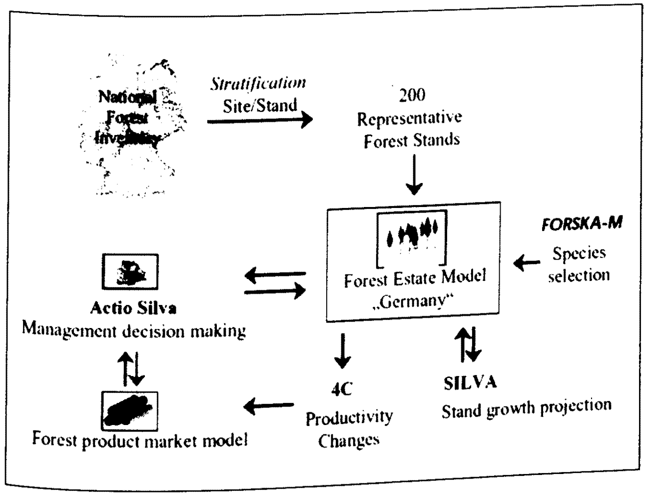

Fig. 1. Model applications in the GFS study. The grey arrows represent model linkages that have only been tested so far; they were not applied in the presented results.

Abb. 1. Modelanwendungen im Projekt Wälder und Forstwirtschaft Deutschlands im Globalen Wandel. Graue Pfeile charakterisieren Modellverknüpfungen, die konzipiert und getestet wurden, aber in den vorliegenden Resultaten nicht zur Anwendung kamen.

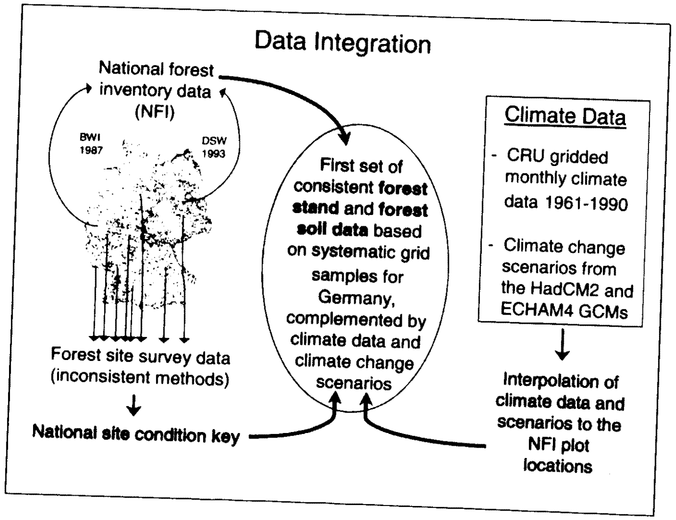

Fig. 2. Overview of the processing of soil and climate data to generate consistent input data for the model applications in the GFS study.

Abb. 2. Übersicht über die Verarbeitung von Boden- und Klimadaten zur Bereitstellung von Modelleingangsdaten im Verbundprojekt.

The distance-dependent and site-sensitive single tree simulator SILVA was first introduced by PRETZSCH (1992) and has been further developed into a flexible tool for different planning tasks in forest management, as a research tool and for educational purposes (KAHN and PRETZSCH 1997, PRETZSCH 1997, BIBER et al. 1998a, PRETZSCH 2002). The simulator applies a spatial modelling approach, which explicitly takes into account single tree competition effects. It has been fitted using long-term experimental plots in pure and mixed stands. SILVA was calibrated for the most important German tree species in mixed and pure stands under a variety of management concepts and operates on 5 – year time steps. The site sensitivity of SILVA is provided by its site-growth-potential submodel (KAHN 1994), which relies on a set of nine climate and soil parameters. The mathematical model is formulated according to a quasi-causal approach but fitted statistically. The data used for this fit represents wide-spread climate-growth relationships including data from research plots from the Atlantic and Baltic coasts in Northern Germany to the Swiss Alps. The SILVA model has been shown to be applicable in some areas of climate impact research (BIBER et al. 1998b, PRETZSCH et al. 2000, PRETZSCH and UTSCHIG 2000). It was applied in the GFS study to project forest growth and timber production in the forest estate model (DUSCHL and SUDA 2002), to investigate silvicultural adaptation strategies in forest management (DÖBBELER and SPELLMANN 2002), and in a sensitivity study that also included the calculation of economic parameters (PRETZSCH and ĎURSKÝ 2002).

Forest patch models (BOTKIN et al. 1972, BUGMANN 2001) can be used to evaluate species competitiveness and growth potential under different climatic conditions in managed forest ecosystems (LINDNER 1999, LINDNER et al. 2000). In this study, the environmental response functions of the model FORSKA-M (LASCH et al. 1999, LINDNER 2000) were applied to generate fitness indices to select suitable species for stand regeneration under changing environmental conditions (LASCH et al. 2002).

To analyse physiological effects of climatic change on tree growth (e.g. increased water use efficiency of plants under increasing CO_2, ABER et al. 1995), detailed process-based simulation models including a mechanistic formulation of tree growth are needed (RYAN et al. 1996). In this study, the model 4C ('FORESEE' – Forest Ecosystems in a Changing Environment) was used to investigate the sensitivity of forest growth to changes in CO_2, temperature, and precipitation (LASCH et al. 2002). The model simulates the establishment, growth and mortality of tree cohorts based on physiological processes such as photosynthesis, respiration, and carbon allocation.

2.2 Simulating decision-making in forest management

The composition and structure of German forests has been strongly influenced by human activities for several centuries. As past forest management practices have determined our current species composition, decision-making of present day owners and managers of the forests play a crucial role in shaping the future forest composition. Decision-making thus is a key factor that needs to be considered in the assessment of climate impacts in managed forests. Linking model approaches from social and economic sciences with natural sciences was a special challenge in the GFS study. While economic modelling has already developed many quantitative approaches based on optimisation techniques, qualitative studies dominate in the social sciences. There are approximately 1.3 million forest owners in Germany with diverse ideas on how to manage their forests. Such diversity causes problems for optimisation approaches, because they need to presume a deterministic behaviour of the forest manager. We analysed possible consequences of management decisions by linking a forest scenario model with the forest growth simulator SILVA. The forest scenario model describes alternative management strategies, which reflect the different values and ideals of the forest owner, and projects their consequences into the future using the forest growth simulator. Since legal regulations and statutory orders restrict decision-making in German forestry, one objective of the GFS study was to gather and to operationalise them in such a way that they could also be applied in the integrated assessment.

2.3 The integrated assessment approach of the GFS study

Based on a stratification of forest inventory data (POTT and FABRIKA 2002), a method was developed that allows representative forest estate models to be generated for different spatial or focal units (DUSCHL 2001, DUSCHL and SUDA 2002). The forest estate models consist of 200 model stands, which are described in terms of one principal tree species, one secondary, and one tertiary admixed species. In addition, the model stands are allocated to a particular age class and state of thinning and regeneration. The site characteristics comprise water supply, altitude, grade of continentality and nutrient supply. This study focused on the forest estate model 'Germany', other examples include a forest estate model for the Black Forest or the small privately owned forestlands of Bavaria (DUSCHL 2001). Coupled to the forest estate model is the forest scenario model ActioSilva, which models the decision-making processes of a forest enterprise. Different management objectives can be specified and several economic indices are calculated in ActioSilva (DUSCHL and SUDA 2002). The stand simulator SILVA 2.2 (PRETZSCH 2002) is also embedded into the forest estate model. It projects the stand growth of the 200 representative model stands into the future. After every time step of five years, inventory data of the forest estate model and economic indices are updated in ActioSilva. Based on these and the chosen management strategy, ActioSilva selects stands for harvesting and thinning. When stands are regenerated under changing environmental condition, the fitness indices calculated by LASCH et al. (2002) can be used to select new species for stand regeneration. Also directly coupled to the forest estate model is the forest product market model (BARTELHEIMER 2002). This model computes prices for different timber assortments, which are needed in ActioSilva to calculate costs and revenues for alternative management decisions. Test simulations showed, however, that the current design of the simulation experiment caused problems in the forest product market model, because the flow of timber generated by the forest estate model fluctuated too strongly, causing unrealistic price developments, especially for those species with only a few representative stands in the model estate (e.g. oak (*Quercus* spec.). Consequently, the current results of the forest estate model were based on the assumption of constant timber prices. On the other hand, the forest product market model had to use other estimates of the effects of climate change on the supply of timber (BARTELHEIMER 2002).

2.4 Linking process oriented studies regarding impacts on forest genetics and forest productivity to the integrated assessment study

Adaptation and adaptability of Norway spruce (*Picea abies* (L.) Karst.) under changing climatic conditions was investigated by analysing individual genetic variability with data from the international IUFRO Norway spruce provenance experiment. The objective here was to provide parameters with genetic variability to the models that were applied in the GFS study. However, the implication for the explanation of model uncertainty in the SILVA and 4C models has not yet been analysed. A greenhouse experiment with European beech (*Fagus sylvatica* L.) provenances was analysed to study the response of different provenances to increased temperature and elevated CO_2 (KRIEBITZSCH et al. 1998). Furthermore, simulation studies were run to estimate possible effects of an increasing annual mean temperature and a decreasing annual mean precipitation on the genetic structure based on inventories of isozyme gene loci for Norway spruce (LIESEBACH 2002).

Increasing atmospheric CO_2 concentrations are expected to enhance forest productivity (JARVIS 1998, NORBY et al. 1999), rising temperatures could result in positive growth responses, especially in high latitudes and high elevations (JARVIS and LINDER 2000, RUSTAD et al. 2001), or in growth declines because of drought effects, especially near the southern distribution limit of drought-sensitive tree species (HANSON and WELTZIN 2000). In this study, the process-based forest patch model 4C was used to investigate the sensitivity of forest growth to changes in CO_2, temperature, and precipitation (LASCH et al. 2002). The results of this sensitivity analysis will be compared in this paper with the simulation results of the forest estate model, and some sources of uncertainty in the current climate impact assessment will be discussed.

2.5 Forest Management under Climate Change

One prerequisite for the simulation and evaluation of management strategies is the quantitative description of silvicultural concepts. A methodological approach was developed that defines target basal areas in relation to the possible maximum stand density for different forest development stages (DÖBBELER and SPELLMANN 2002). This approach was applied with the forest growth simulator SILVA 2.2 to investigate the effects of alternative treatments on growth, stability and structure for the representative stands of the forest estate model under current climate and under the HadCM2 climate change scenario.

Many management decisions are made at the level of management units. Therefore the forest estate model and the forest scenario model ActioSilva were developed to analyse the effects of different management scenarios at this strategically important scale (DUSCHL and SUDA 2002). Stand characteristics such as age class, state of thinning, and regeneration are considered in the model initialisation, and different management strategies are applied with the growth simulator SILVA 2.2 to project the forest estate into the future. ActioSilva then comprehensively analyses the effects of the simulated stand treatments and the regeneration of harvested sites at the level of the forest estate and uses this information in the further decision-making process. Three prototypical management strategies, investment oriented management (MS1), net forest yield oriented management (MS2), and semi-natural management (MS3) span a wide range of management objectives. MS1 – MS3 have been devised as somewhat extreme strategies, which are not meant to represent current management practices. Most management strategies in reality try to base their decision-making on multiple objectives and thus can be considered mixtures of the three extreme strategies applied in the GFS study.

To simulate the management of legally established conservation areas under changing climatic conditions a method was developed based on content analyses of regulations in various conservation area categories (SCHLOTT and GUNDERMANN 2002). This approach could be combined with MS3 to simulate a management strategy that optimises ecosystem services from the forest.

2.6 Effects of climate change on Forest Product markets

No existing timber market model was found to be applicable to simulate the effects of climate change on German forest product markets. A new simulation model was developed using components of the System Dynamics approach of SCHWARZBAUER (1993) for the Austrian timber market. It describes processes of timber supply from domestic forestry and foreign countries, and the demand for wood by four sectors of the forest industry: saw mills, producers of boards, pulp mills, and energy production, as well as the foreign demand. The timber demand by tree species, log sizes or pulpwood depends on the demand for forest products and the price relations between different timber assortments. The demand for forest products is determined by external forecasts of consumption (BAUDIN and BROOKS 1995). Based on the demand and supply data production decisions are made by the forest industry. In each period the actors on the markets offer or request the products in fixed and elastic shares. The intersection of the aggregated demand and supply functions determines the market equilibrium and the price for the products in a simulation period. Differences in the demand and supply from the equilibrium volume are accounted for by accumulation or reduction of stocks. At the end of each simulation period of one year, the prices of the products are modified by world market prices, which are based on external projections. In this study current world market prices were assumed throughout the projection period.

To simulate the effect of climate change on the forest product market, national wood supply under the HadCM2 and ECHAM4 climate change scenarios was estimated from forest productivity changes calculated with 4C (LASCH et al. 2002).

3 Key results

The simulations of the forest estate model under current climate emphasise how strongly management strategies influence forest development (Figure 3). Whereas MS2 led to relatively small changes in the species composition with a constant share of broadleaved and

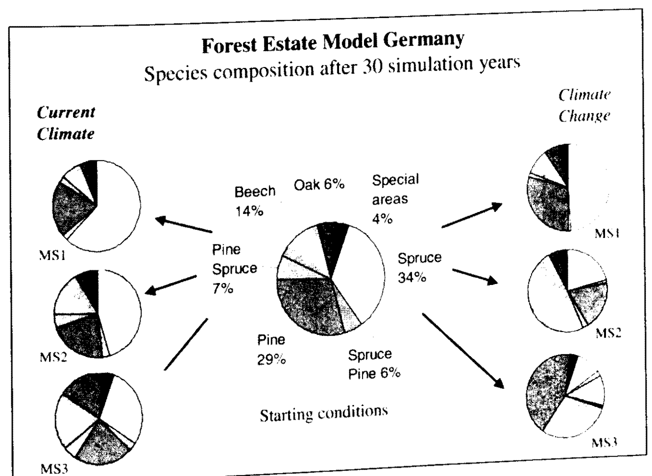

Fig. 3. Simulated changes in species composition of the forest estate model after 30 years under current climate and the HadCM2 climate change scenario. MS1 – MS3 are three prototypical management strategies: MS1 – investment oriented management, uses the Faustmann Formula to determine harvest age; MS2 – net forest yield oriented management, maximizes the financial yield of the forest without consideration of interest rates; MS3 – seminatural management, uses MS2 with restriction to species of the Potential Natural Vegetation.

Abb. 3. Veränderungen der Baumartenzusammensetzung im Modellbetrieb Deutschland nach 30 Simulationsjahren unter heutigen Klimabedingungen und dem Klimaänderungsszenario HadCM2. MS1 – MS3 sind drei extreme Waldbewirtschaftungsstrategien: MS1 – Investitionsorientierte Bewirtschaftung; MS2 – Waldreinertragsorientierte Bewirtschaftung; MS3 – Naturgemäße Bewirtschaftung.

coniferous stand types, and little change in average stocking or age class distribution, MS1 resulted in drastic changes of the forest estate. The species composition shifted to a much larger dominance of spruce, average stocking declined sharply to 35 % of the initial values, and the age class distribution was skewed towards the youngest age classes.

Under the HadCM2 climate change scenario, the proportion of spruce stands was reduced significantly with all three management strategies compared to current climate. In MS1 spruce was partly replaced by pine (*Pinus sylvestris* L.), and the average cut and the net revenues from the harvested wood declined by approximately 15 %. With MS2 and MS3 there was a strong shift from coniferous to deciduous stand types. The average cut doubled compared to the current climate and the age class distribution changed into a skewed distribution similar to the one that MS1 produced for both current and future climate conditions. Average stocking under MS2 and MS3 was reduced by approximately 30 %, but stocking under MS1 was much lower still.

MS3 simulated a marked increase in the share of oak and beech under both climate scenarios. Oak stands covered more than 40 % of the forest estate in the HadCM2 scenario. In contrast, with MS1 and MS2 oak played only a very minor role.

Dobbeler and Spellmann (2002) investigated the growth of Norway spruce, Scots pine, and beech with and without management under current climate and the HadCM2 scenario. Climate change affected the growth of Norway spruce on all sites, leading to a lower height and diameter increment, but the results showed large regional differences (Table 1). In the forest growth regions (FGR – see Table 1) 54 and 18, climate changes resulted in longer thinning periods and delayed target diameter harvesting. In contrast to Norway spruce, Scots pine showed a positive growth response to the changed climatic conditions (Table 1). In FGR 9 and FGR 64 the thinning period was reduced by two simulation periods, and in FGR 65 target diameter harvesting started several simulation periods earlier. Beech did not show significant changes under the climate change scenarios, except for a slightly decreased height performance in one FGR. Stem density and diameter increments remained unaffected.

Table 1. Climate change induced growth changes of spruce and pine in different forest growth regions. Simulation results of the SILVA model without thinning treatments (Dobbeler and Spellmann 2002)

Tabelle 1. Durch Klimaänderung bedingte Wachstumsveränderungen von Fichte und Kiefer in ausgewählten Wuchsgebieten. Simulationsergebnisse des Models SILVA ohne Durchforstungseingriffe (Dobbeler and Spellmann 2002)

Species	Forest growth region	Total Growth over 100 simulation years (m^3/ha)		Relative Growth Change (%)
		Current Climate	HadCM2 Climate Change Scenario	
Spruce	14 ('Niedersächsischer Harz')	2136	2081	−3
Spruce	18 ('Sauerland')	2082	1586	−24
Spruce	54 ('Tertiäres Hügelland')	2758	1801	−35
Spruce	77 ('Thüringer Gebirge')	2010	1830	−9
Pine	9 ('Ostniedersächsisches Tiefland')	1092	1245	+14
Pine	64 ('Nordbrandenburger Jungmoränenland')	1072	1318	+23
Pine	65 ('Mittelbrandenburger Talsand- und Moränenland')	847	1353	+60

Pretzsch and Ďursky (2002) studied the sensitivity of spruce to climatic change using SILVA at representative sites for the 17 eco-regions described in Wolff (2002). Only one mountainous region showed an increase in the projected growth of spruce, whereas in the other regions total increment declined by 2 % – 58 %. For three eco-regions, the model projected environmental conditions outside of the ecological amplitude for spruce

(lowlands in Northeast Germany and Rhineland-Westphalia, as well as the Rhine valley with adjacent hilly areas). An investigation of the competitive relations between spruce and beech indicated that beech gained in competitive strength and productivity on sites where the growth of spruce was declining.

The productivity analyses with the process-based forest model 4C in the 12 FGR of the forest estate model showed productivity gains of stands under the HadCM2 scenario and losses in productivity in regions with decreasing precipitation under the ECHAM4 scenario (Lasch et al. 2002). The differences between the climate scenarios can be explained by contrasting precipitation projections. While precipitation under HadCM2 generally increased, there were regional differences in predicted precipitation in the ECHAM4 scenario, which caused productivity gains for some spruce stands and losses for broad-leaved species.

The model sensitivity study at a pine site (Kienhorst, Brandenburg) using 4C with different temperature and precipitation scenarios demonstrated the high sensitivity of forest growth in dry areas like the northeastern German lowlands to changes in the water balance. This was confirmed by the calculated fitness index, which underlined the primary importance of drought stress for the overall fitness of the four species beech, oak, pine, and spruce in the state of Brandenburg.

Provenances of Norway spruce generally showed a wide range of growth variations on sites of international provenance trials with different climatic conditions. Whereas a few provenances seemed to be well adapted to all sites, the majority performed well only under specific site conditions (Liesebach et al. 2001).

In the base run of the forest product market model, the potential German timber production was 58 million m^3 per year, which is 16 % above the current volume estimate of 50 million m^3. The climate change scenarios resulted in a projected production of 61 million m^3 under HadCM2 and 53 million m^3 under ECHAM4. The increasing production figures under all climate and socio-economic development scenarios are caused by the external forecast for wood product consumption, which predicts a much sharper rise in

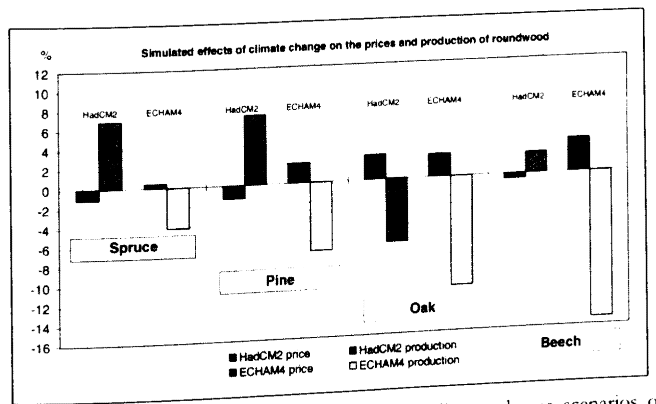

Fig. 4. Effects of changes in forest productivity under two climate change scenarios on simulated roundwood production and prices on the forest products market. Results of the forest product market model FPMM (Bartelheimer 2002) using productivity changes calculated with the 4C model for the HadCM2 and ECHAM4 climate changes scenarios (Lasch et al. 2002).

Abb. 4. Auswirkungen der durch Klimaänderungen bedingten Produktivitätsveränderung der Hauptbaumarten auf die simulierte Rundholzproduktion und die damit verbundenen Holzmarktpreise. Die Ergebnisse des Holzmarktmodells FPMM (Bartelheimer 2002) wurden mit Produktivitätsveränderungen kalkuliert, die vom Modell 4C für die HadCM2 und ECHAM4 Klimaänderungsszenarien berechnet wurden (Lasch et al. 2002).

demand compared with the simulated growth of supply. The results of the scenario simulation with the forest products market model indicate how the different sectors of the forest industry could change their production in correlation with the expected consumption and demand and the supply of timber from domestic forests. Under the simulated climate change scenarios no dramatic development is expected for the forest sector. The changes in the roundwood distribution showed larger fluctuations in single years as a consequence of the model intrinsic decision rules to extend or cut back the production after price changes. However, on average over the 30 years of the simulation period the production volume of most forest products responded in the same order of magnitude as the +9 to −6 % changes in projected forest growth. Scenarios with increased yield, like HadCM2 for spruce, pine, and beech, led to lower roundwood prices. On the other hand, reduced growth yields a lower supply of roundwood on the market, which results in higher prices (Figure 4). But the increase of the prices is not large enough to fully compensate the losses of the forest enterprises.

4 Discussion

4.1 Integrating inter-disciplinary impact assessments

A key to the successful integration of different disciplines in integrated climate change assessments is the concept of balance (LINDNER et al. 2002). One important aspect is that as far as possible all disciplines should be treated at the same level of precision or generality. However, balance often proves difficult to achieve, because the disciplines involved in an integrated assessment study do not start at a comparable stage of methodological development. For example, growth and yield research has a long tradition in the development of simulation models and forest inventories have been specifically devised to calculate the potential yield of the forest in terms of wood supply. Other disciplines are less advanced in this respect. The various ecosystem services from forests have only recently been generally recognised as an important objective of multifunctional forest management, and consequently they are more difficult to represent in an integrated assessment study. The GFS study tried to put emphasis on a balanced representation of the different effects of climate change. To better analyse the socio-economic implications of climate change, new simulation approaches had to be developed. Some of these approaches will need further evaluation and refinement, but this should not impair the achievements of the GFS network. Firstly, the database of consistent gridded forest inventory data and site information proved reliable and useful for the application of simulation models at the national scale. Secondly, the impact assessment integrated a broad range of disciplinary simulation approaches that is unparalleled in current forest impact studies. Thirdly, this was achieved in a well co-ordinated modelling framework that has great flexibility for the investigation and assessment of environmental changes and their effects on forests in Germany.

4.2 Scenario analysis enables impact assessments in complex systems

The complexity of processes and interactions in the forest sector under changing environmental conditions makes simplifications necessary in the design of any integrated forest impact assessment study. The inter-disciplinary GFS team jointly decided on how complex the integrated assessment system should be, what simplifications were necessary, and how the disciplinary components could be incorporated in the methodology. Numerous scenarios were considered in the different disciplinary assessments of the GFS study: (i) scenarios of climate change, (ii) alternative management strategies, (iii) economic scenarios affecting timber prices, and (iv) scenarios determining the area of forests with protection status and management constraints. Theoretically, the integrated assessment methodology

would allow for a comprehensive analysis of hundreds of combinations of these different scenarios. However, reducing the number of individual scenarios for each component of the assessment seemed to be the only practical way to implement this broad integrated assessment study. This study focused on a set of two major scenario combinations, one for the current climate baseline, and a second for one climate change scenario. Time constraints led to the investigation of climate sensitivity under the assumption of constant timber prices (i.e. baseline economic development), focusing on only three extreme management strategies. Individual groups investigated the effects of alternative scenarios (e.g., alternative economic scenarios under the current and future climate, or alternative climate change scenarios under the baseline economic scenario), but there clearly is demand for additional investigations, especially including more climate change scenarios and alternative management strategies in the integrated assessment. Furthermore, the method to simulate management in conservation areas (SCHLOTT and GUNDERMANN 2002) was not yet implemented in the management strategy focusing on ecosystem services.

4.3 Different simulation approaches to investigate ecological effects of climate change

Two different forest growth models were applied in the GFS study. SILVA 2.2 and 4C are fundamentally different approaches to simulating forest growth. SILVA has a strong empirical basis of long-term forest growth measurements on experimental plots. The climate sensitivity of SILVA is due to its site-potential model (KAHN 1994). The data used for the calibration of this submodel incorporates a very broad range of climatic conditions. The current climate and corresponding forest growth in Germany is covered very well by this data. However, the projected temperature increase of 3 – 4 °C leads for many locations to conditions that are at the border or even beyond the limits of the current range of climatic conditions. 4C, on the other hand, is based on physiological growth processes and uses a mechanistic representation of carbon assimilation and allocation to calculate tree growth. Both models have strengths and limitations. Over the last few years, process-based simulation models like 4C have begun to be used for practical application in forest management (MÄKELÄ et al. 2000, JOHNSEN et al. 2001), but their strength is still in research applications. 4C has been validated with good results against measured soil water data, short-term carbon fluxes, and forest growth data – but on relatively few sites only. While the accuracy of model projections with SILVA 2.2 has been determined for applications under current climate by comparison to observations (PRETZSCH 2002), we lack data to evaluate the long-term model performance under changing climatic conditions.

SILVA includes a series of quasi-causal environmental response functions, one of which is modelling the temperature response of different tree species. This response function generally shows a decline of the growth potential beyond a certain species-specific temperature optimum (e.g. growing season mean temperature of 14.3 °C for spruce). Similar parabolic response functions have been used in many forest simulation models to project possible impacts of climate change (e.g. SOLOMON 1986, PASTOR and POST 1988, KIENAST 1991), but several authors claimed that these functions overestimate the impacts of climate change (e.g. LOEHLE and LEBLANC 1996, SCHENK 1996, BUGMANN 2001). Empirical data show little evidence for a decrease in tree growth under higher temperatures. For example, FELBERMEIER (1993) found that beech in Bavaria did not show declining growth potentials close to its warm distribution limit. LOEHLE (2000) demonstrated contrasting climate impact projections using an asymptotic and a parabolic temperature response functions in the SORTIE model. He argued that the asymptotic function (i.e. the growth potential increases from minimum temperature requirements to a maximum at a species-specific level without a decline under warmer temperatures) produced more realistic results.

It is important to separate the fundamental and the realised ecological niche of tree species (AUSTIN and SMITH 1989, ELLENBERG 1996). Our knowledge about the actual physiological growth limits of tree species (i.e. the fundamental niche) is relatively poor. While the parabolic response function assumes that the fundamental ecological niche of a species can be estimated from the observed growth range (i.e. the realised niche), the above-mentioned studies suggest that the southern limits of plant species are determined by plant competition or drought effects, rather than by direct physiological growth responses to temperature gradients.

4.4 Model comparisons can help to assess uncertainties in climate impact assessments

Model comparisons can provide indirect evidence about the plausibility of simulation approaches to the assessment of climate change impacts (CRAMER et al. 1999, KRAMER et al. 2001). In the following we compare results from the application of the two different simulation models 4C and SILVA. In the 4C model simulations, a combination of temperature increase with stable or decreasing precipitation led to decreasing forest productivity, whereas temperature increase with sufficient water supply did not have a negative effect. Under the HadCM2 climate scenario, 4C simulated a positive growth response of spruce in all forest growth regions, because the increasing precipitation more than balanced the enhanced evaporative demand that was caused by the temperature increase. In contrast, SILVA generally projected declining productivity for spruce under this scenario. The regional comparison of simulated climate impacts shows that SILVA projected large negative effects on sites with higher temperatures under current climate, regardless of the changes in precipitation. This is especially noticeable in FGR 54 "Tertiäres Hügelland", currently one of the most productive forest regions in Germany. According to the SILVA simulation, spruce stands in this region would decline drastically in productivity. In comparison, the 4C results showed increasing productivity in both climate change scenarios for this region, because both climate models, especially the HadCM2, projected higher precipitation.

Several physiological responses of trees to the changing climate, such as the compensation of growth declines in the summer months through an extended growing season with higher productivity, especially in early spring, or increasing water use efficiency under higher atmospheric CO_2 contents, are not captured by the empirical simulation approach. The comparison of the different model results suggests that the negative impacts under the HadCM2 climate change scenario may be overestimated by SILVA. On the other hand, the comparison of different scenarios in 4C indicates that under a future climate with less precipitation there would be much greater risk of growth declines. Thus the results of SILVA and the forest estate model need to be interpreted with care, especially for those sites which are relatively close to the warm distribution limit of the current species composition. However, the simulated magnitude of the climate change impacts is not unrealistic, because similar growth responses would be expected for ecologically more stressful climate change scenarios (like the ECHAM4), or because of additional factors that were not included in this assessment study. In fact, it is well known that spruce is especially susceptible to insect outbreaks on warm and dry sites outside its natural range. Moreover, there is an indication that the risk of insect outbreaks will increase under a warming climate (VOLNEY 1996, SIMBERLOFF 2000). The consideration of the consequences of a warmer climate on the frequency and severity of disturbances such as bark beetle outbreaks (cf. LEXER and HONNINGER 1998), storm events (PETERSON 2000) or forest fires (GERSTENGARBE et al. 1999, FLANNIGAN et al. 2000) poses an important challenge for future investigations of climate change impacts in the forest sector.

To evaluate socio-economic effects of climate change it is crucial to calculate changes in forest growth and yields in terms of different timber assortments. Site-sensitive growth simulators like SILVA 2.2 are currently the best choice for such growth projections. However, we need to be aware of the limitations of the models and consider them in the interpretation of the results. An alternative approach was used in the EU funded project "Long-term effects of climate change on European forests: impact assessment and consequences for carbon budgets" (LTEEF II), where process-based model projections were used to change the empirical growth functions implemented in the EFISCEN forest scenario model (KARJALAINEN et al. 1997, KARJALAINEN et al. 2002, KRAMER and MOHREN 2001). KARJALAINEN et al. (2002) projected overall gains in productivity of 8 % for German forests, under the same HadCM2 climate change scenario that was applied in this study. Their simulation showed, however, that the increase of growing stocks would decline later in the 21st century, because of unfavourable changes in the age structure of the national forest resources. These results are similar to the 4C projections for the same climate change scenario, and they underline the importance of longer-term simulation studies to assess the likely consequences of climate change.

4.5 Climate change impacts on forest management and economic implications

The impact assessment with the forest estate model showed that changing climatic conditions will lead to shifting species preferences in forest management, provided that the same rules are used in the decision-making process. However, this analysis was based on only one climate change scenario. The results of the sensitivity analysis with the 4C model stress the importance of analysing different climate change scenarios in forest impact assessments, because the differences in the projected changes in precipitation between two GCMs may result in opposed growth responses. Currently, the uncertainty about the future trends in precipitation is high, especially with respect to Central European regions for which different GCM scenarios projected both positive and negative trends (HOUGHTON et al. 2001).

The present study focused on a small number of sites in the integrated assessment. Only forest types that cover more than 5 % of the national forest area have been considered and thus the species composition of the forest estate model represents not more than 60 % of the whole forest area in Germany. Nevertheless, the results are meaningful, because they cover the most common, and economically most significant forest types. It is important to recognise, however, that the climate change impacts could be more severe on marginal sites and at the ecotones of the current forest species distribution (NEILSON 1993, SPIECKER et al. 2000). The next logical step would be to extend the analysis to include regional and local variability in the forest conditions. DUSCHL (2001) computed forest estate models at different aggregation levels. Figure 5 shows the forest estate model 'Bavaria'. Compared to the national forest estate model there is a greater dominance of coniferous species and a larger number of mixed species stands in the federal state Bavaria. The variability of site conditions increases. For example, spruce stands originating from 5 different forest growth regions include poor, medium, and rich site fertility, and span four different water supply categories from slightly moist to stagnic. It is conceivable that the analysis of climate change impacts at the regional level would yield more diverse results, especially at the level of a forest growth region or forest growth area, where site variability and local species combinations can be better represented. Certainly, such an application of the methodology at the regional scale would produce results that could be transferred more easily into management decision support for forestry practice, because the structure of the forest estate model would likely show greater similarity with the regionally occurring forest management units. While there is little hope that uncertainties regarding regional climate projections can be removed in the near future, there is considerable evidence that the sensitivity of the forests to climate change differs between regions. Therefore, spatially explicit impact assessments are needed to analyse regional differences of impacts across Germany, using a larger set of regional climate projections.

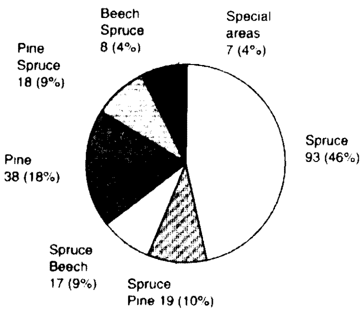

Fig. 5. The species composition of the forest estate model 'Bavaria', representing 72 % of the approx. 2.5 million ha of forest in the state Bavaria (DUSCHL 2001). The numbers indicate the number of stands for each forest type and their relative share (in brackets).

Abb. 5. Baumartenzusammensetzung im Modellbetrieb „Bayern", der 72 % der ungefähr 2,5 Millionen ha umfassenden Waldfläche in Bayern repräsentiert (DUSCHL 2001). Dargestellt sind die nach Baumarten aufgeteilte Anzahl der Modellbestände sowie ihre Flächenanteile (in Klammern).

The first results of the newly developed forest product market model suggest that the economic implications of forest growth changes induced by climate change are not negligible, although the uncertainties in the scenario projections were high. This underlines the importance of considering both ecological and economic impacts of climate change. The GFS study successfully developed a simulation approach that integrates these different impacts at the national scale for Germany. Further investigations are recommended to extend and validate the methodological approach.

5 Conclusions

One of the objectives of the GFS study was to demonstrate the potential of the currently available data and simulation approaches to investigate the effect of global change on German forests and forestry. Climate impact research is a relatively new scientific discipline and it is not surprising that we still face considerable limitations in our current methodologies. Nevertheless, we believe that the GFS study furthered our understanding of how climate change affects the forest sector and how we can assess these impacts with integrated simulation approaches. The GFS study was the first integrated climate impact assessment study for the German forest sector and it demonstrated that interdisciplinary collaboration is important in synthesising our current knowledge about the effects of climate change on forests and the forest sector. Comprehensive assessments like this are useful for decision-making in forestry in the face of changing environmental conditions. Our results indicate that impacts of climate change in Germany will be site- and species-specific. Negative growth changes are likely to occur on sites where drought stress under climate change increases. Where precipitation is not the limiting growth factor, however, forest productivity may also increase. Overall, the projected impacts of climate change on the German forest sector are very sensitive to the amount and annual distribution of precipitation in the future climate. Compared to the baseline projection of the forest product market model for the national timber production under current climate, climate change resulted in an increase of timber production by 5 % in the HadCM2 and a decrease of 9 % in the ECHAM4 climate change scenario. We conclude that climate change constitutes a manageable risk to the German forest sector. However, especially under unfavourable site conditions significant negative ecological and socio-economic impacts are possible. Many open questions remain to be investigated in further research efforts. From our experience in the GFS study we identified the following research needs:

Experimental data on responses of forest ecosystems to increasing temperatures, CO_2, and changing precipitation are key for validating our existing simulation approaches of climate change impact assessments. Whereas our understanding of CO_2 effects is constantly improving, very few experiments have observed long-term effects of climate warming on forest growth and soil carbon dynamics in pure and mixed stands. Particularly important is a better understanding of species-specific responses at the current southern distribution limits of economically important tree species. In this context disturbance effects need to be considered in integrated assessment studies, and the impacts of climate change on the frequency and intensity of disturbances such as storms, insect outbreaks, and forest fire deserves further investigation.

The integrated assessment approach of the GFS study should be elaborated in several ways:

- the national application should be complemented by regional impact assessments (i) to analyse the climate sensitivity of a broader variety of forest types under different site conditions and (ii) to investigate possible regional differences in climate change impacts
- the applicability of results in decision-making could be increased by studying more realistic management strategies in the forest scenario model ActioSilva
- investigating more scenario combinations, including different climate change scenarios, would help to capture better the uncertainties in the impact assessment
- transient simulation studies over longer time periods than 30 years are needed to evaluate long-term consequences of alternative management strategies
- the coupling of the forest estate and forest product market models should be improved to investigate feedbacks between forest growth changes and economics on decision-making in the forest scenario model

The SILVA growth simulator should be tested with alternative environmental response functions. The effect of the current temperature response function outside of the climatic conditions for which growth measurements are available could be analysed in comparison with simulations using an asymptotic response function.

Spatially explicit model applications with the 4C and SILVA models across all forest inventory plots are important to identify particularly vulnerable regions, forest types and site conditions. More species and a choice of forest management strategies need to be incorporated into the process-based model approach of 4C and the model should be tested against observed data at a greater number of intensively measured research plots (e.g. of the European Level II program). Existing forest inventory systems in Germany should be continued and further developed according to present and future demands.

Adaptation and mitigation strategies in forest management require more research. The potentials of forest management to increase carbon storage in forests to mitigate climate change should be investigated with more detail. Forest policy studies should investigate how suitable adaptation measures could be successfully implemented into forestry practice to ensure the sustainability of forest utilisation under changing environmental conditions.

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