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German Forest Sector under Global Change: An Interdisciplinary Impact Assessment

Wälder und Forstwirtschaft Deutschlands im Globalen Wandel: Eine interdisziplinäre Wirkungsanalyse

MARCUS LINDNER and WOLFGANG CRAMER

Summary

The assessment of potential impacts of climate change on forests and forestry requires an interdisciplinary approach. This paper introduces the collaborative „German Forest Sector under Global Change“ study, which was designed to demonstrate the potential of such an analysis. The objective of the study was to investigate the nature and extent of possible impacts of global climate change on forests and the forest sector in Germany. Our paper describes the overall project philosophy, as well as the scenarios for changing climate and forest management that were used in the research network. The assessment was based on inventories of national forest resources as well as on several simulation models: the forest growth simulator SILVA 2.2, the forest patch models FORSKA-M and 4C, the forest scenario model ActioSilva, a forest estate model and the forest product market model FPMM. From forest inventory data 200 forest stands were selected to represent structure and composition of forests in Germany. Stand development was projected 30 years into the future under both current and changed climatic conditions. For each forest inventory plot, climate data were generated corresponding to current climate (1961–1990) and two climate change scenarios based on the projections of the HadCM2 and ECHAM4 global circulation models for the years 2041–2070. For Germany, both climate change scenarios show an increase of 2.9–3.6 °C in mean temperature, but rainfall differed markedly between scenarios. While the HadCM2 model projects on average a 20 % increase in annual precipitation in this region, the ECHAM4 model projects reduced precipitation, along with a greater temperature increase during the summer months. Three prototypical management strategies are used for the assessment, spanning a triangle including pure economical orientation, optimised timber volume yield, and priority to ecosystem services from the forest. These extreme management strategies were devised to encompass the great variety of different management objectives that are encountered in German forestry. The paper ends with an outlook on the remaining papers of this journal supplement, which presents the results of three years of work of the research network, documenting significant progress in quantitative forest science and global change research in Germany.

Keywords: climate change, forest sector, impact assessment, simulation study, integrated modelling

Zusammenfassung

Die Analyse und Bewertung der Auswirkung von Klimaveränderungen auf die Forstwirtschaft bedarf eines interdisziplinären Forschungsansatzes. In diesem Beitrag wird das Verbundprojekt „Wälder und Forstwirtschaft Deutschlands im globalen Wandel: Strategie für eine integrierte Wirkungsanalyse und -bewertung“ vorgestellt, welches die Möglichkeiten eines solchen Ansatzes ausleuchten sollte. Das Ziel des Projektes war die Abschätzung und erste Bewertung möglicher Auswirkungen von Klimaveränderungen auf die Wälder und die Forstwirtschaft Deutschlands. Die übergeordnete Philosophie der Untersuchung wird beschrieben, sowie die im Verbundvorhaben verwendeten Klima- und Bewirtschaftungsszenarien. Die Studie nutzte die vorhandenen Daten der westdeutschen Bundeswaldinventur und des ostdeutschen Datenspeicher Waldfonds sowie neu zusammengestellte Standortsinformationen und verwendete in der integrierten Wirkungsanalyse mehrere Simulationsmodelle: den Waldwachstumssimulator SILVA 2.2, die Waldentwicklungsmodelle FORSKA-M und 4C, den Forstbetriebssimulator ActioSilva, ein Realwaldmodell und das Holzmarktmodell FPMM. Die Waldinventurdaten wurden stratifiziert, um 200 Waldbestände für das die gesamtdeutschen Waldflächen repräsentierende Realwaldmodell Deutschland zu generieren. Die Entwicklung der Modellbestände wurde unter gegenwärtigem und verändertem Klima 30 Jahre in die Zukunft simuliert. Für jeden Inventurpunkt wurden Klimadaten für das heutige Klima generiert (entsprechend den Mittelwerten der Jahre 1961–1990) sowie zwei Klimaänderungsszenarien berechnet basierend auf den Projektionen der globalen Klimamodellen

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HadCM2 und ECHAM4 für die Jahre 2041–2070. Für die Inventurpunkte weisen beide Klimaszenarien einen Anstieg der Jahresmitteltemperaturen um 2.9–3.6 °C auf, unterscheiden sich aber deutlich bezüglich der Entwicklung der Niederschläge. Während das HadCM2 einen Anstieg der mittleren Jahresniederschlagssumme um 20 % projiziert, fällt das Klimaszenario des Modells ECHAM4 ökologisch ungünstiger aus – mit weniger Niederschlag und höheren Temperaturen innerhalb der Vegetationszeit. Drei alternative Bewirtschaftungsstrategien wurden im Projektverbund untersucht. Diese wurden bezüglich ihrer Zielsetzungen als Extremtypen formuliert, die mit ihrer Ausrichtung auf Gewinnmaximierung, Maximierung des Waldreinertrags oder naturgemäße Waldbewirtschaftung die meisten der in der vielgestaltigen deutschen Forstwirtschaft praktizierten Bewirtschaftungsstrategien umfassen. Zum Abschluss wird ein Überblick über die weiteren Beiträge in diesem Sonderheft gegeben, in denen die Resultate aus drei Jahren Forschungsarbeit des Projektverbundes vorgestellt werden. Die Zusammenstellung dokumentiert deutliche Fortschritte in der modellgestützten Erforschung der Auswirkungen des Globalen Wandels auf die Forstwirtschaft in Deutschland.

Schlüsselwörter: Klimaveränderung, Forstwirtschaft, Klimawirkungsforschung, Simulationsstudie, Integrierte Modellierung

1 Introduction

The link between rapidly increasing emissions of greenhouse gases from fossil fuel combustion, cement production, and tropical deforestation and changing climate and the responses of terrestrial biota has now been studied for more than 15 years. The most recent report of Working Group II of the Intergovernmental Panel on Climatic Change (McCarthy et al. 2001), as well as other summaries (e.g. Parry 2000), not only conclude that there now is evidence of a human influence on climate and ecosystems, but also show an increasing degree of confidence in the quantitative assessments of these changes. Ecosystems and the services they provide are therefore likely to change significantly in the years and decades to come, and public and private management of these resources must prepare its response to this challenge. While global mean temperature is rising and is expected to continue to do so, particularly at higher latitudes, there is greater uncertainty about the nature of changes in rainfall. It is unlikely, however, that rainfall (and moisture availability for plants) would be unchanged in a changed climate. Assessments of climate change impacts therefore need to cover a range of conditions including both drier and moister climates.

Impacts on forests need to be assessed not only with respect to climate, but also for the direct effects of increased atmospheric CO_2, for atmospheric pollutants, and changing land management. At temperate latitudes, the primary factors of forest response are recognised as enhanced growth of trees due to both warming and increased atmospheric CO_2 concentrations, possibly reduced growth in areas where moisture could become limiting, and changes in the natural disturbance regime, which could result in increased wildfire events, insect infestations, and storm damages.

For the actual change in forest appearance in a country like Germany, factors of socio-economic change will play an important role. Forests managed for timber production may face significantly different yield potential, with consequent changes in management regimes, concerning rotation periods or even species selection. At a broader scale, the market for timber products is changing due to multiple reasons, and this, too, can affect the selection of management strategies for a given stand. An assessment of climate change impacts in forestry therefore requires an interdisciplinary approach that combines quantitative determination of potential yield under alternative management objectives with implications for ecosystem functioning, social benefits of forests, effects on timber supply, and the performance of the forest industry. Only on this basis a development of mitigation strategies against possible adverse effects of climate change is feasible.

German forestry research has a long tradition of comprehensive forest ecosystem studies. Approximately 20 years ago, the „Waldsterben“ dominated the headlines of press media and many research projects on the possible causes and consequences of forest dieback were initiated. There has been unquestionable progress in the understanding of basic forest ecosystem processes (e.g. Ulrich 1987, Schulze and Ulrich 1991, Umweltbundesamt 1996), but many impact mechanisms remained unclear, and the success of this research campaign with respect to resolving the environmental problem was disputed by some authors (Herkendell 1998, Wentzel 2002). One of the shortcomings of the research on the „Waldsterben“ was a lack of co-ordination between different projects (Reuther 1999).

An integrative project aiming at systems analysis and modelling only started in the mid 1990's (Umweltbundesamt 1996), i.e. at about the same time when global climate change and its possible impacts on ecosystems entered the research agenda. There was thus only little experience and limited funding available for new, comprehensive and integrated research projects on the impacts of climate change on forests and forestry in Germany. Therefore, the German Federal Ministry of Science and Technology favoured a co-ordinated approach focussing on modelling and the application of models to existing data sets rather than more basic research on the processes underlying ecosystem responses to climate change. The compilation of papers in this publication represents the results of three years of work by the research network „German Forest Sector under Global Change“ (GFS). In this paper we first give a brief overview of the different impacts of climate change on forests and forestry, before we introduce the research approach and describe some of the data and scenarios that were applied. Finally we give an outline of the remaining papers of this journal supplement, which documents significant progress in quantitative forest science and global change research in Germany. A more detailed evaluation of the applied methodology and a summary of key results are given in the synthesis paper of Lindner et al. (2002[a]).

2 What do we know about the impacts of a changing climate on forests and forestry?

Different processes in forest ecosystems and the forest sector are sensitive to climate change at greatly varying scales; therefore research has addressed a broad range of influencing factors and impacts. Among the first investigations were studies on the impacts of climate change on vegetation composition (Emanuel et al. 1985, Smith et al. 1992, Woodward 1992, Leemans and Vandenborn 1994, Cramer 1996) and forest succession (Solomon 1986, Pastor and Post 1988, Kienast 1991, Prentice et al. 1991, Bugmann 1997, Price et al. 1999). These studies were based on simulation models, which are best suited to investigate the relationships between ecosystem state and climate under equilibrium conditions. The results primarily indicated the potential magnitude of changes, but they have limitations regarding their ability to simulate the timing of the projected changes (cf. Solomon 1997). Furthermore, some important assumptions in these models turned out to be inappropriate, e.g., some temperature response functions, which may lead to overestimated forest responses to climate change (Bugmann et al. 1996, Loehle and Leblanc 1996, Schenk 1996). None of the models included realistic estimates of likely responses in forest management.

Whereas long-term vegetation changes are difficult to measure in the real world, there are many other impacts of climate, which can be observed on shorter time scales. Several studies have shown that the observed increase in temperature has already lead to an extended growing season in temperate and boreal forest ecosystems (Myneni et al. 1997, Menzel and Fabian 1999) and further changes in tree phenology are expected (Kramer et al. 1996, Linkosalo et al. 2000). Changes in temperature, water availability, and atmospheric CO_2 inevitably affect ecosystem processes such as photosynthesis and respiration (Jarvis 1998, Medlyn et al. 1999, Rustad et al. 2001) and thus influence forest productivity (McGuire et al. 1993, Joyce 1995, Cramer et al. 1997, Joyce and Nungesser 2000, Coops and Waring 2001) and forest growth and yield (Woodbury et al. 1998, Hasenauer et al. 1999). Tree responses may vary significantly between provenances (Billington and Pelham 1991, Beuker et al. 1998, Persson 1998, Bigras 2000), but it is not yet known how fast genetic adaptation of tree populations could occur in response to climate change. Increasing temperatures and changed moisture will also modify disturbance regimes (Dale et al. 2001). Possible consequences include more frequent insect outbreaks (Fleming and Volney 1995, Volney 1996) and/or wild fires (Kasischke et al. 1995, Stocks et al. 1998, Li et al. 2000). The effects of climate change on storm frequency and velocity are less understood, but some authors suggest that major weather system movements are shifting and thus storms may cross Central Europe more frequently, especially during the winter months (Werner et al. 2000).

Only recently the implications of changing growth patterns and disturbance regimes on forest management (Kellomäki and Kolström 1993, Lindner 2000, Lindner et al. 2000, Pretzsch 1999, Sabate et al. 2002) and timber markets (Mills and Haynes 1995, Perez-Garcia et al. 1997, Sohngen and Mendelsohn 1998) have become a focus of research. However, there is still a big gap between improved process understanding and forestry practice and consequently great need for decision support at the operational scale (cf. Lexer et al. 2000). In Europe, the first regional climate impact assessments are now becoming available (Lasch et al. 1999, Freeman et al. 2001, Lexer et al. 2002). However, secondary consequences on the forest industry (see Nabuurs and Moiseyev 1999, Mills et al. 2000), the need to adjust forest policies and resource planning, and further implications for social values of forests (Binkley and Van Kooten 1994, Lasch et al. 2002[b]) have not been well studied to date and require further research.

Because of the broad range of possible impacts, there is growing interest to link impact models within forest sector impact studies (Binkley and Van Kooten 1994, Joyce 1995, Winnett 1998, Joyce and Birdsey 2000, Lindner et al. 2002[b]). The majority of these integrated approaches use a chain of two or more simulation models with relatively little interaction between them („soft linkages" according to Cohen et al. 1998). In most cases output from one model (e.g., a vegetation model) is used as input in another (e.g., a timber market model). Direct collaboration between researchers of the different disciplines is often limited and the assessment tools are not always consistent in their underlying assumptions. Lindner et al. (2002[b]) stress the importance of more balanced approaches in integrated forest assessments, requiring closer collaboration across disciplines than before. One such effort is described in the contributions of this journal supplement.

3 The approach of the GFS study

The objective of the GFS research network was to analyse and assess the nature and extent of possible impacts of global climate change on forests and the forest sector in Germany. The assessment was based on existing inventory data of the national forest resources (Wolff 2002) and a suite of different simulation models (see Fig.1). Some of the models had been developed earlier by network members, while others were established during the study. All models, however, were adapted through intensive interaction between network members, and consistency was ensured to the highest level possible.

Three existing and well-tested forest simulation models where used: (i) SILVA (Pretzsch 1992, Kahn and Pretzsch 1997, Pretzsch 2002) to simulate forest growth and yield, as well as several indicators of ecosystem structure and function (Pretzsch et al. 2000), (ii) FORSKA-M (Lasch et al. 1999, Lindner 2000) to analyse species competitiveness, and (iii) 4C (Bugmann et al. 1997, Schaber et al. 1999) to investigate changes in forest productivity under the current and future climate (Lasch et al. 2002[a]). In addition to these three models, a forest scenario model, ActioSilva, was developed to analyse some socio-economic impacts of the projected changes in forest development and productivity (Duschl and Suda 2002). ActioSilva was linked to a forest estate model consisting of 200 forest stands, representing the most important forest types of German forests. Conditions in these forest stands were projected into the future using SILVA 2.2 (Pretzsch 2002) with three different prototypical management strategies (see *data and scenarios* below).

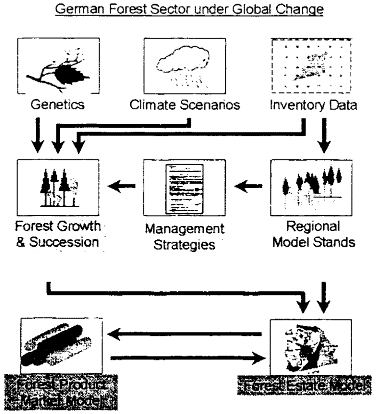

Fig. 1. Project overview – The GFS study used available inventory data and a framework of simulation models to investigate the impacts of climate change on forest succession, growth and yield projections, genetic adaptability of major tree species, decision making in forest management, and forest economics.

Abb. 1. Projektübersicht – die Studie Wälder und Forstwirtschaft Deutschlands im Globalen Wandel verwendete verfügbare Inventurdaten und unterschiedliche Simulationsmodelle um die Auswirkungen globaler Klimaänderungen auf das Waldwachstum, die Waldsukzession, die genetische Anpassungsfähigkeit der Hauptbaumarten, das Entscheidungsverhalten in Forstbetrieben sowie die Forstökonomie zu untersuchen.

A forest product market model (Bartelheimer 2002) was linked to ActioSilva in order to calculate prices for timber assortments as a basis for the decision-making process in forest management, and to analyse possible responses of the forest products markets to climate change. Furthermore, the genetic adaptability of major forest tree species was analysed based on simulation modelling and an assessment of forest provenance trials. A special focus of the simulation studies with SILVA was the investigation of silvicultural response strategies to climate change (Döbbeler and Spellmann 2002), and particular attention was paid to the management of conservation areas (Schlott and Gundermann 2002).

Because of the high diversity of German forests and the complexity of interactions between site conditions, climate, forest growth, forest management and socio-economic implications, we did not adopt a bottom-up approach based on the forest growth projections for individual stands (Lexer et al. 2002) or spatially explicit representations of forests in grid based approaches (cf. Joyce and Nungesser 2000). Instead, we linked the different simulation models to a forest estate model that is representing the most important forest types under typical site conditions in Germany. The forest stands of the forest estate model were selected from the forest inventory data using a stratification for species composition, regional abundance in forest growth regions („Wuchsgebiete", characterizing ecologically similar growth conditions (Arbeitskreis Standortskartierung der Arbeitsgemeinschaft Forsteinrichtung 1985)), site conditions, and climate (Pott and Fabrika 2002). For each stratum, one representative model stand was assigned to an inventory plot location as close as possible to the centre of the stratum with respect to altitude and continentality. Only forest types covering more than 5 % of the forest area in Germany were included in the forest estate model. Consequently, the assessments in this journal supplement focus on the most common and economically most important forest types of Germany, representing 60 % of the whole forest area in Germany. However, the methodology is not restricted to an application at the national scale. It would be possible to apply the same simulation approach also at the regional scale, e.g. for different states or eco-regions within Germany. Such a regional application could include much more detail and a greater diversity of forest types, leading to more realistic forest estate models and climate change impact assessments.

4 Data and Scenarios

4.1 Linking soils information and forest inventory data

The forest simulation models applied within the impact assessment need a variety of input data, including initial tree species composition, soils, and climate. Different forest inventory sources had to be used for former East and West Germany. The „Datenspeicher Waldfonds" was used to extract forest stand and soil data for East Germany. However, this data base is not geo-referenced and thus was linked to the systematic grid of the Ecological Forest Condition Control (ÖWK; Wolff 2002). Since the national forest inventory of West Germany did not include sufficient information on site and soil characteristics, it was necessary to link the forest inventory to site classification and soil maps from different sources. The federal structure of Germany complicated this task, because each federal state has developed more or less unique systems for forest site characterisation and classification. Wolff et al. (1999) developed a method to estimate standardized soil parameters from state level soil survey data, which was used to generate the first consistent nationwide forest resource database with both forest inventory and soils data for Germany (Wolff 2002). However, soil-horizon-specific parameters required for the simulation models 4C and FORSKA-M were not available from the forest soil surveys. Therefore, an overlay of the digital soil map BÜK 1000 (Federal Institute for Geosciences and Natural Resources, Hannover) with the inventory points was generated and soil profile data of the dominant soil types for each soil series were used to estimate the soil information for the models 4C and FORSKA-M (cf. Lasch et al. 1999).

4.2 Climate data

For each forest inventory plot, climate data were generated for current climate (i.e. 1961–1990) as well as for two climate change scenarios. The data for the current climate were extracted from the CRU (Climatic Research Unit, University of East Anglia, Norwich) climate data, which includes monthly average values of mean temperature, temperature range, precipitation, and cloud cover. The data originate from measured station data that were interpolated on a grid with 0.5° × 0.5° spatial resolution (Hulme et al. 1995, New et al. 1998). To capture regional differences in climate, including effects of elevation (which are represented in the CRU data only at the coarse grid level), a three step procedure was developed: First, long-term monthly mean climate data of the Cramer – Leemans Climate data base for 1931–1960 (Leemans and Cramer 1991) were interpolated to the 7230 national forest inventory plots as well as to the 0.5° × 0.5° grid of the CRU data set, using a thin-plate spline interpolator (Hutchinson 1995), accounting for latitude, longitude, and elevation at each location. Second, time series of anomalies between the long-term monthly mean climate (1931–1960) and the CRU data set of monthly values from 1901–1995 were calculated for each grid cell. Third, at each inventory point, the time series of anomalies of the corresponding grid cell was added (temperature) or multiplied (precipitation) to the local long-term monthly mean climate data. Hence, all inventory plots within the same 0.5° × 0.5° grid cell show the same temporal pattern of climate data, but the regional differences of the long-term mean climate data were preserved.

Climate change scenarios

Climate change scenarios were generated based on two different, well established transient general circulation model (GCM) projections, (i) the HadCM2-SUL simulation (Hadley Center, Mitchell et al. 1995), and (ii) the ECHAM4/OPYC3 simulation (Max Planck Institute Hamburg, Roeckner et al. 1996). Both projections are based on the IPCC „business-as-usual" greenhouse gas emission scenario IS92a (Houghton et al. 1995), which incorporates an exponential increase of atmospheric CO_2 concentration between the years 1990 (350 μmol mol^{-1}) and 2100 (700 μmol mol^{-1}). The HadCM2-SUL simulation includes the cooling effects of sulphur aerosols on climate, whereas this effect is not included in ECHAM4/OPYC3. The scenario data set provides monthly values of minimum and maximum temperature, precipitation, sunshine and global radiation at 3.75° × 2.5° spatial resolution.

While these relatively recent transient climate scenario projections appear more realistic than the equilibrium climate change scenarios of older GCM experiments (Grassl 2000), it was not possible to apply the full transient projections in the integrated assessment. The time horizon of the linked model projections was limited to 30 years, because of the computationally demanding simulation runs. The forest inventory data available for model initialisation dated from 1990, and therefore a transient climate change scenario projection over 30 years would have ended already in 2020, which we assumed to be too early to capture a clear climate change signal in long-lived forest ecosystems. Furthermore, decision-making in European forest management should take into account possible long-term changes in forest growth, because these constitute risks for the next forest generation, which is usually managed with a 80–150 year rotation time (cf. Lindner et al. 2000).

To account for these considerations, it was decided to analyse the sensitivity of the forest sector to a hypothetical, instantaneous new climate. The forest simulation models were initialised with forest inventory data of 1990 (the same as under current climate) and were run with an equilibrium climate corresponding to the climate conditions of the late 21st century. The second IPCC climate change assessment report suggested that the most probable range of greenhouse gas induced temperature increase by the year 2100 would be 1.0–3.5 °C globally, with similar trends for Central Europe (Kattenberg et al. 1996). Because the two selected GCM projections showed a much higher increase in temperature for 2100 (between 5° and 6 °C), the climate change scenarios adopted for this study were based on GCM data for the simulation years 2041–2070, corresponding to a temperature increase of 2.9–3.6 °C.

The characteristics of the climate change scenarios are summarised in Tab. 1 and Fig. 2. The two scenarios differ from each other especially with regard to precipitation. The HadCM2 scenario projects, across all inventory plots, on average a 20 % increase in annual precipitation (between 26 mm and 396 mm), with more pronounced increases during the winter months and little change over the vegetation period. The ECHAM4 scenario projects significantly less precipitation in the future climate than HadCM2, on average 10 mm less than under current climate, with regional differences between −143 mm and +118 mm. Evaporative demand during the summer months is further intensified in ECHAM4, because this scenario projects greater temperature increase during the summer months compared to the HadCM2, which shows much larger warming over the winter months (Fig. 1). Consequently the ECHAM4 climate scenario is ecologically more stressful. Changes in the variability of precipitation (e.g. longer dry-spells and more frequent high rainfall events) would also affect forest growth but such changes were not considered in this study. It is important to note that it is currently not possible to evaluate, which of the existing climate change projections is most plausible for the

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[1] The annual precipitation sum was included in the tables 2 and 3 for comparison, this variable is not required for the SILVA model.

Table 1. Long term annual mean temperature and precipitation sum under the climate scenarios used in the German Forest Sector under Global Change study (averages of all 7230 German forest inventory plots) for the reference periods 1961–1990 (current climate) and 2041–2070 (HadCM2 and ECHAM4 climate change scenarios)

Tabelle 1. Langjährige Jahresmitteltemperatur und Niederschlagssumme in den Klimaszenarien des Projektes Wälder und Forstwirtschaft im Globalen Wandel (gemittelt über alle 7230 verwendeten Waldinventurpunkte). Bezugsperiode 1961–1990 (heutiges Klima) bzw. 2041–2070 (HadCM2 und ECHAM4 Klimaänderungsszenarios)

	Average annual mean temperature (°C)	Average annual precipitation sum (mm)
Current Climate	8.2	731
HadCM2	11.5	880
ECHAM4	11.4	721

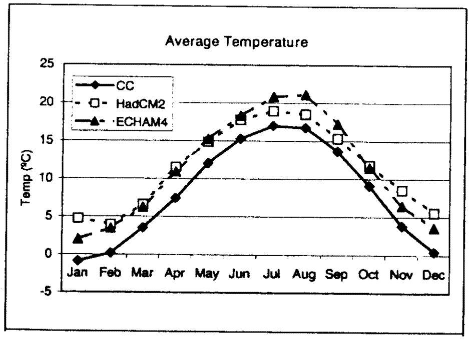

Fig. 2. Long term monthly mean temperatures of the current climate (CC) and the two climate change scenarios (HadCM2 and ECHAM4). The values are averages over all 7230 German forest inventory plots included in the German Forest Sector under Global Change study. The long term monthly means were calculated from 1961–1990 (current climate) and 2041–2070 (climate change scenarios), respectively.

Abb. 2. Langjährige Jahresmitteltemperatur unter heutigem Klima (CC) und zwei Klimaänderungsszenarien (HadCM2 und ECHAM4). Die Werte wurden über alle 7230 im Projektverbund berücksichtigten Waldinventurpunkte gemittelt. Bezugszeitraum 1961–1990 (CC) bzw. 2041–2070 (Klimaänderungsszenarien).

study region. Because of the remaining uncertainty in climate projections it is highly recommended to use more than one climate change scenario in climate impact assessments.

Downscaling of the climate scenario to the site level

Two data sets were prepared, (i) 30 years of daily weather data based on the GCM output of 2041−2070, and (ii) aggregated climate indices (see Tab. 2) for the same reference period. GCM results were scaled from grid cells to sites by calculating, for monthly time steps, the difference of each parameter between the time period 2041−2070 and the average values of the reference period 1961−1990. This procedure generated a time series of anomalies, which was then added to the average values of the CRU data of the same reference period. Anomaly calculations were made again by subtracting and adding the values of the different parameters, except for rainfall, where this was done by division and multiplication. This procedure forces the main spatial pattern of observed climate to be maintained while applying the broad trends of climate change as simulated by the GCM.

Table 2. Aggregated climate variables for the forest growth regions in which representative forest stands were selected for the forest estate model 'Germany' under current climate: mean annual temperature (T_{ann}), mean temperature of the growing season (May 1 − September 30) (T_{grow}), mean annual precipitation sum (P_{ann}), precipitation sum of the growing season (P_{grow}), number of days with mean temperature above 10 °C (D_{T10}), and temperature range (T_{amp}, the difference between mean temperature of the warmest and the coldest month). Reference period 1961−1990

Tabelle 2. Aggregierte Klimaindizes für die im Modellbetrieb Deutschland enthaltenen Wuchsgebiete: Jahresmitteltemperatur (T_{ann}), Mittlere Temperatur in der Vegetationszeit (1. Mai bis 30. September; T_{grow}), mittlere Jahresniederschlagssumme (P_{ann}), mittlere Niederschlagssumme in der Vegetationszeit (P_{grow}), Anzahl der Tage über 10 °C (D_{T10}) und Temperaturamplitude (T_{amp}, die Differenz zwischen der Monatsmitteltemperatur des wärmsten und des kältesten Monats). Heutiges Klima, Referenzperiode 1961−1990

Forest Growth Region[1]	**T_{ann} (°C)**	**T_{grow} (°C)**	**P_{ann} (mm)**	**P_{grow} (mm)**	**D_{T10} (N)**	**T_{amp} (°C)**
9	8.5	15	667	308.8	162	16.8
10	9.3	15.4	748	325.6	173	16.1
11	8.2	14.6	693	359.2	160	17.1
14	6.6	13.2	708	319.5	137	17.3
18	8.1	14.3	873	366.1	156	16.4
41	8.3	15.6	678	366.7	164	19.8
53	7.5	14.2	913	467.1	152	18.2
54	8.3	15.3	850	462.6	163	18.7
64	8.7	15.7	556	277.3	167	18.4
65	9.0	16	570	276.6	172	18.4
77	6.3	13	843	394.5	136	17.5

[1] Forest Growth Regions: 9 − 'Ostniedersächsisches Tiefland', 10 − 'Westfälische Bucht', 11 − 'Weserbergland', 14 − 'Niedersächsischer Harz', 18 − 'Sauerland', 41 − 'Frankenalb und Oberpfälzer Jura', 53 − 'Schwäbische Alp', 54 − 'Tertiäres Hügelland', 64 − 'Nordbrandenburger Jungmoränenland', 65 − 'Mittelbrandenburger Talsand- und Moränenland', 77 − 'Thüringer Gebirge'. The location of the forest growth regions is shown in Wolff (2002, Fig. 2).

The monthly climate data of the inventory plots was disaggregated to daily values using the C2W weather generator (Bürger 1997), which had been fitted with climatological station data of the weather station in Potsdam. A stochastic procedure derived from monthly or seasonal anomalies is applied to disaggregate long-term climatological means. The aggregated values of the stochastic 'weather' reproduce the mean temperature values of the input data exactly (Erhard et al. 2001). However, the stochastically generated precipitation sums were 0−6.8 % (average 3.4 %) lower than the measured values.

Calculation of aggregated climate parameters

For each inventory plot, aggregated climate indices as required for the SILVA model were calculated for the current climate (1961−1990) and for the two climate change scenarios. Tab. 2 shows the values for the sites of the forest estate model Germany under current climate, and Tab. 3 presents the climate change signals (i.e. the differences compared to the current climate) of the two investigated climate change scenarios for the same selection of sites. There are considerable regional differences in both

climate change scenarios. For example, the increase of the mean temperature of the growing season varies between 1.6 and 2.9 °C in the HadCM2 scenario and between 2.9 and 4.1 °C in the ECHAM4 scenario. It should be noted that this increase in precipitation is spatially and temporally not evenly distributed. In some forest growth regions 50 % of the additional precipitation occurred during the growing season (forest growth region 41, 54, 64), whereas in other regions only 20−25 % of the precipitation increase was projected to fall between May and September (forest growth region 9, 11, 18). The ecologically most significant climate change with large temperature increase and lower than average precipitation during the growing season was projected by both climate change scenarios for the forest growth regions 10 ('Westfälische Bucht') and 18 ('Sauerland').

Table 3. Climate change signals for the forest growth regions in which representative forest stands were selected for the forest estate model 'Germany', calculated from the HadCM2 (Had2) and ECHAM4 (ECH4) climate change scenarios in comparison to the current climate: mean annual temperature (T_{ann}), mean temperature (T_{grow}) of the growing season (), mean annual precipitation sum (P_{ann}), precipitation sum of the growing season (P_{grow}), number of days with mean temperature above 10 °C (D_{T10}), and temperature range (T_{amp}). Reference periods 1961−1990 (current climate) and 2041−2070 (climate change scenarios)

Tabelle 3. Klimaänderungssignale berechnet für die im Modellbetrieb Deutschland berücksichtigten Wuchsgebiete: Jahresmitteltemperatur (T_{ann}), Mittlere Temperatur in der Vegetationszeit (T_{grow}), mittlere Jahresniederschlagssumme (P_{ann}), mittlere Niederschlagssumme in der Vegetationszeit (P_{grow}), Anzahl der Tage über 10 °C (D_{T10}) und Temperaturamplitude (T_{amp}). Differenzen zwischen den Klimaänderungsszenarien (Bezugszeitraum 2041−2070) und dem heutigen Klima (1961−1990)

Forest Growth Region	T_{ann} (°C)		T_{grow} (°C)		P_{ann} (mm)		P_{grow} (mm)		D_{T10}		T_{amp} (°C)	
	Had2	ECH4	Had2	ECH4	Had2	ECH4	Had2	ECH4	Had2	ECH4	Had2	ECH4
9	3.2	3.1	2.3	3.3	92	−6	21.9	−33.3	50	37	−1.8	1.1
10	3.1	3.4	2.9	4	187	−26	50	−40.7	53	42	−0.4	1.9
11	3.0	3.1	2.1	3.5	117	−34	27.6	−48	42	35	−2.4	1.2
14	2.9	2.9	1.8	3.2	174	31	45.3	−31.4	36	35	−2.4	1.1
18	3.4	3.5	2.5	4.1	219	−38	45	−54	53	42	−1.7	2
41	3.5	3.4	1.7	3.6	145	7	74.6	10.1	48	37	−4.6	0.8
53	3.3	3.4	2	4.1	172	−2	80.9	0.3	44	38	−3.9	1.8
54	3.5	3.6	2.1	4.1	160	23	80.3	18	48	41	−4.1	1.4
64	2.9	2.9	2.4	2.9	71	10	39.7	−24	36	32	−1.4	0.3
65	3.0	2.9	2.3	3	49	−20	24.1	−36.6	39	32	−1.9	0.3
77	3.3	3.0	1.6	3.3	238	19	86.5	−10.5	41	34	−3.1	1.3

4.3 Selection of management scenarios

Forests in Germany include public, municipal and privately owned forestlands, and the size of management units greatly varies from 1 ha to more than 1000 ha. Forest management strategies are also diverse, often influenced by the local experiences of several generations of foresters. Since only a small number of different management strategies could be analysed in the integrated assessment, it was decided to select three extreme management scenarios for the forest estate model (Duschl and Suda 2002):

1. An investment oriented management strategy that uses the classical Faustmann formula (Faustmann 1849) to determine the harvest schedule with the objective to maximize the land rent of the forest estate. In this strategy forest stands that yield less than an interest rate of 4 % are harvested and the stands which yield the lowest interest are cut first.
2. The net financial yield oriented management aims to maximize the forest rent. It uses the culmination of mean annual value increment of the forest stand without consideration of interest rates as criteria for harvest scheduling (Davis and Mason 1966), which leads to significantly longer forest rotation periods. In forest regeneration the tree species with the highest revenue are selected.
3. The semi-natural management strategy is focusing on a natural forest composition and favours the tree species of the potential natural vegetation (cf. Tüxen 1956), with consideration of responses of the species composition to climate change.

The third strategy can be combined with forest conservation and/or management restrictions on fractions of the total forest area (Schlott and Gundermann 2002). The three strategies can be characterized as prototypes spanning a triangle including extremely economical orientation focussed on land rent, optimised forest rent, and priority to ecosystem services from the forest (Figure 3). In reality, most applied management strategies are mixtures of the three extremes, and thus the impacts of climate change under such mixed strategies are expected to be intermediate between the analysed scenarios.

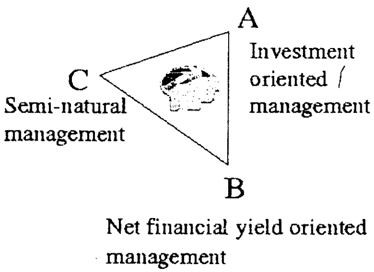

Fig. 3. Three different management strategies were investigated: A – the investment oriented management strategy uses pure economic reasoning; B – the net financial yield oriented management aims to maximize volume yield; C – the semi-natural management strategy is focusing on a natural forest composition and other ecosystem services from the forest.

Abb. 3. Drei verschiedene Bewirtschaftungsstrategien wurden untersucht: A – die investitionsorientierte Bewirtschaftungsstrategie strebt eine Gewinnmaximierung an, B – die waldreinertragsorientierte Bewirtschaftungsstrategie maximiert den Bestandeswertzuwachs, C – die naturgemässe Bewirtschaftungsstrategie fördert eine natürliche Baumartenzusammensetzung und die Schutz- und Sozialfunktionen des Waldes.

5 Outline of the journal supplement

The collection of papers in this journal supplement is based on the results of the research network GFS, which was funded by the Federal Ministry of Education and Research from July 1997 to June 2000. Wolff (2002) documents the data base of the research project and describes how site information data were linked to the stand inventory data to generate the first consistent national data set that includes both stand inventory and site data. Pretzsch (2002) introduces the forest growth simulator SILVA 2.2, which was applied in the project to simulate the growth of representative stands under different climate and management scenarios. Several methodological developments were necessary to run the growth simulator with forest inventory data within the framework of the forest estate model. Döbbeler and Spellmann (2002) introduce a methodology to simulate silvicultural treatments with the growth simulator SILVA 2.2 under current and changing climatic conditions. Ďurský (2002) developed a system of regional tariffs to estimate missing stand level variables from the inventory data. The generation of stand structures to initialise the growth simulator was reported elsewhere (Pommerening 2000, Pommerening et al. 2000). Pott and Fabrika (2002) stratified the forest inventory data to select representative forest stand – site combinations and show how simulation results were visualised by means of a linkage of the growth simulator to a Geographic Information System. The last paper focusing on the growth simulator SILVA 2.2 presents a sensitivity study about the effects of climate change on the growth of Norway spruce in Germany (Pretzsch and Ďurský 2002). In the GFS study, forest growth and socio-economics are linked in a forest estate model. Duschl and Suda (2002) describe this model and simulate three different management strategies under current and changing climatic conditions. The paper by Schlott and Gundermann (2002) discusses how forest management in conservation areas can be analysed under climate change. Liesebach (2002) reports a simulation study on possible effects of climatic change on the genetic structure based on inventories of isozyme gene loci in provenance trials of Norway spruce. Lasch et al. (2002[a]) investigate changes in forest productivity of the four major forest species in Germany under two climate change scenarios and analyse how the changing climate affects species competitiveness. The effects of the changes in forest growth and forest management on the German forest products markets were simulated by Bartelheimer (2002). The final paper attempts to give a synthesis of the most important research results of the GFS study and concludes with an outlook on further research needs in forest related climate impact research in Germany (Lindner et al. 2002).

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