Alternative Forest Management Strategies under Climatic Change – Prospects for Gap Model Applications in Risk Analyses

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The projected global climate change will influence growth and productivity of natural and managed forests. Since the characteristics of the future regional climate are still uncertain and the response of our forests to changes in the atmospheric and climatic conditions may be both positive or negative, decision making in managed forests should consider the new risks and uncertainties arising from climatic change, especially if the rotation periods are long. An extended version of the forest gap model FORSKA was applied to simulate the forest development at 488 forest inventory plots in the federal state of Brandenburg, Germany, under two climate and three management scenarios. The transient growth dynamics from 1990 to 2100 were investigated at four sites in different parts of the state, representing the variability of environmental and forest conditions within Brandenburg. The alternative management strategies led to distinct differences in forest composition after 110 years of simulation. The projected climate change affected both forest productivity and species composition. The impacts of alternative management scenarios are discussed. It is concluded that the extended forest gap model can be a valuable tool to support decision making in forest management under global change.

Keywords adaptation and mitigation strategies, climate change, forest management, forest succession model, FORSKA
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1 Introduction

Recently there has been increasing awareness of the fact that the projected changes of climate will not only impact natural forest ecosystems, its consequences will also affect managed forests and the forest management strategies applied in these forests (Kellomäki and Kolström 1993, Landsberg et al. 1995, Lindner 1999, Lindner 2000). The temperate forests of Central Europe are managed with long rotation periods, usually between 80 and 200 years. Climate models currently project a temperature increase of approximately 1.5–3 K within the next 50 to 100 years (Kattenberg et al. 1996). Thus the majority of present day forests will probably live long enough to grow under significantly changed climatic conditions. However, the precise characteristics of the future climate are still uncertain, especially at the regional scale. Furthermore the response of our forests to changes in the atmospheric and climatic conditions may be both positive or negative, depending on the local environmental conditions (Joyce 1995, Bugmann 1997, Lasch et al. 1999, Ryan et al. 1996, Kellomäki et al. in press, Sohngen et al. 1999). Therefore decision making in forest planning is facing considerable risks and uncertainties.

Forest gap models have played a prominent role in investigating the possible impacts of climate change on forests (e.g. Solomon 1986, Pastor and Post 1988, Kienast 1991, Prentice et al. 1991, Botkin and Nisbet 1992, Bugmann 1994, Shugart and Smith 1996). Whereas the majority of investigations to date have been restricted to unmanaged forests, the investigations of Kellomäki and Kolström (1993) and Lindner (1999, 2000) showed that these models are also valuable for the investigation of possible impacts of climate change in managed forests. This paper describes recent applications of the gap model FORSKA (Prentice et al. 1993, Lindner 2000) as a tool to support decision making under climatic change.

2 Methods

In this study a modified version of the forest gap model FORSKA (Prentice et al. 1993) was used. FORSKA simulates growth, regeneration and mortality of individual trees on small forest patches and was used successfully to simulate forest dynamics in Scandinavia (Leemans 1992), Canada (Price and Apps 1996) and north-east Germany (Lindner et al. 1997a, Lasch et al. 1999). The current model version, FORSKA-M, includes a modified height growth function and management subroutines (Lindner 2000); a multi-layer soil percolation model was implemented and the model runs with daily time series of climate data (Lasch et al. 1999). Scenarios of the current climate and a climatic change scenario representing a temperature increase of 1.5 K have been produced using a multi-variate statistical analysis of observation data from several meteorological stations in the state of Brandenburg (Werner and Gerstengarbe 1997). The climate data include time series of daily temperature (°C), precipitation (mm) and relative sunshine duration (%) for 40 stations in or around the state of Brandenburg.

Three different management scenarios were investigated, one traditional and two adaptive management scenarios. The adaptive management scenarios make use of tree-specific response functions for various climatic factors and soil fertility to select favourable species depending on the environmental conditions. FORSKA-M includes climate sensitive response functions to account for the effects of thermal limitations (e.g., minimum winter temperature, length of the vegetation period) and drought stress on tree growth and regeneration, and the effects of temperature on photosynthesis and respiration (Prentice et al. 1993). Soil fertility is a static site parameter which in the current model version is not influenced by climate (Lindner et al. 1997a).

Management in FORSKA-M consists of thinnings, harvesting, and regeneration. In this study, thinnings depended on the height growth of dominant trees and after the stand reached 10 m of height, thinnings were scheduled at least every 20 years. Thinning intensity was determined by basal area values given in East German yield tables for beech (*Fagus sylvatica* L.), and Scots pine (*Pinus sylvestris* L.) (Lembcke et al. 1975; Dittmar et al. 1986). The values for beech were assigned to all shade tolerant species, for other species the values of Scots pine were used. Harvesting occurred either when the mean diameter of the 100 largest trees per ha exceeded a prescribed harvest diameter or when the age of these trees reached the end of the rotation period. The three management scenarios differed from each other in the species preferred for the stand regeneration:

1. The traditional forest management favoured economically important species which dominated the stand before harvesting. Sapling establishment rates for species without mature individuals in the stand before harvesting were only 2% of the normal values for climax species and 10% for pioneer species, whereas in standard gap model runs unrestricted seed availability is assumed for all species. If regeneration was not successful, pine was additionally planted until the density reached 4000 saplings/ha.
2. The adaptive forest management of the second management scenario favoured the climatically best adapted species. The adaptation of individual tree species to the prevailing climate was estimated using the aggregated response functions of the FORSKA-M model which where described above. When stand regeneration occurred the three best adapted species were planted with 1333 saplings/ha.
3. The third management scenario aimed at maximised species diversity and in this scenario all climatically well adapted species were regenerated. Climatic adaptation was estimated as before. Additionally two tolerance thresholds were introduced to identify species with high and low drought risk under the prevailing climate at a site (Lindner 2000). A species was assumed to be well adapted if the drought stress index was greater than the high drought risk threshold. All well adapted species were planted with density N_{sap}:

$$N_{sap} = \frac{4000}{N_{spec}} \tag{1}$$

where N_{spec} was the number of well adapted species at the site.

Planting of selected species in the three management scenarios differs from the ordinary regeneration function in FORSKA-M, because the environmental response functions which usually reduce the number of successful saplings were not applied to actively regenerated saplings.

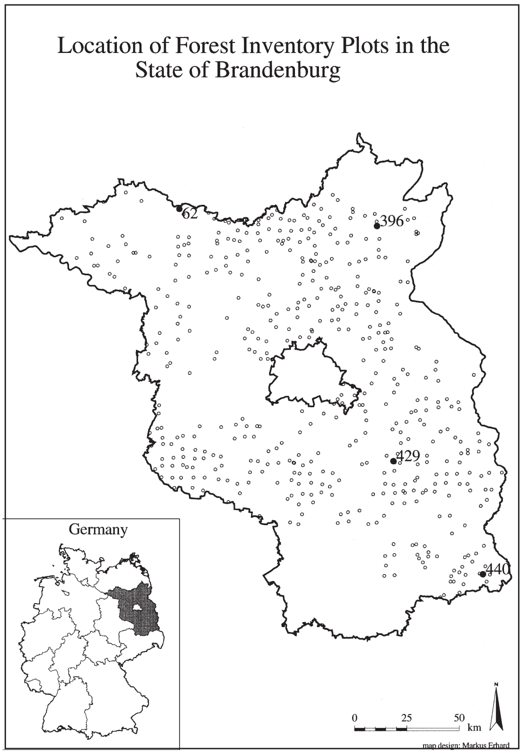

Fig. 1. Location of the State of Brandenburg and the 488 investigated forest inventory plots. The sites where transient simulation runs have been analysed are marked with numbers.

FORSKA-M was applied at 488 forest inventory plots of the state of Brandenburg (see Fig. 1). The study area is situated in north-eastern Germany. At present, forests cover 37% of the territory, i.e. about 1.1 Mio ha. The state lies in the transition zone from maritime to subcontinental climate, and associated to this is the natural distribution limit of beech. The present species composition is strongly dominated by Scots pine, whereas under natural conditions broadleaved species, e.g. beech, oak (*Quercus robur* L. and *Q. petraea* (Matt.) Liebl.), hornbeam (*Carpinus betulus* L.), and lime (*Tilia cordata* Mill.) would prevail. For each forest inventory plot the model was initialised using data generation routines described in Lindner (2000). Soil data were taken from a digital map (Federal Institute for Geosciences and Natural Resources, Hannover 1995) which was stored in a geographical information system (GIS). Climate data were assigned from the nearest of the 40 climatological stations for which climate scenarios have been generated. The simulation period was 110 years from the year 1990 to the year 2100. The species composition was calculated as an average of the years 2080–2100 from 10 replicated simulation runs at every site. It was classified into 15 forest types by the dominant species with respect to standing biomass, similar to the classification of the German Forest Inventory.

3 Results

3.1 Transient Forest Dynamics

Fig. 2 shows the results of transient simulation runs at four different sites in Brandenburg under current climate. Site 62 and 396 were initially dominated by beech and beech-oak stands, respectively, site 429 and 440 were pure stands of Scots pine with an initial age of 67 and 41 years (see Fig. 1 for the location of the sites). Under current climate the traditional management scenario 1 resulted in a stable species composition at all sites except for site 440, where beech, hornbeam and lime established a few years before the harvest of the pine stand. Two stands showed a reduction or stagnation of volume growth after stand initialisation. The simulated biomass at the end of the simulation period was generally lower than at the beginning. At site 62 beech was dominating also under the management scenarios 2 and 3, whereas at the other sites both alternative management scenarios resulted in a shifting species composition. Mainly birch and oak were favoured under management scenario 2, between three and six different species were simulated with management scenario 3.

At most sites the simulated climatic change resulted in a reduction of simulated biomass (Fig. 3). There was relatively little impact on simulated species composition at site 429 and 440, whereas at the other two sites the share of beech declined strongly, especially under the management scenarios 2 and 3. At the site 62 there was a strong increase in biomass after the decline of beech. Both birch under management scenario 2 and the mixed sycamore (*Acer pseudoplatanus* L.) -hornbeam-lime forest under management scenario 3 showed a higher productivity than beech under current climate. The simulated shift in species composition influenced also the timing of cuttings. For example, birch dominated stands were simulated with a lower rotation period under management scenario 2.

Table 1. Simulated new forest composition on 488 inventory plots after 110 simulation years under different climate and management scenarios.

Forest type	Current climate			Scenario +1.5K		
	Management 1	Management 2	Management 3	Management 1	Management 2	Management 3
Pure Scots pine	154	0	1	236	0	4
Mixed pine-broadl.	189	9	184	132	20	131
Beech forests*	29	15	50	0	2	0
Oak forests**	30	234	86	29	286	145
Mixed oak-pine	3	55	34	12	90	40
Birch forests	32	147	1	35	65	0
Hardwoods***	30	20	118	23	16	151
Other forests	14	0	5	10	0	0
Bare patches	7	8	9	10	9	17

Management 1: traditional management; Management 2: favour climatically well adapted species; Management 3: maximise species diversity.
* pure and mixed stands pooled; ** pure and mixed oak-broadleaved stands pooled; *** forests dominated by *Acer* spec., *Carpinus betulus*, *Tilia cordata* or *Ulmus glabra*.

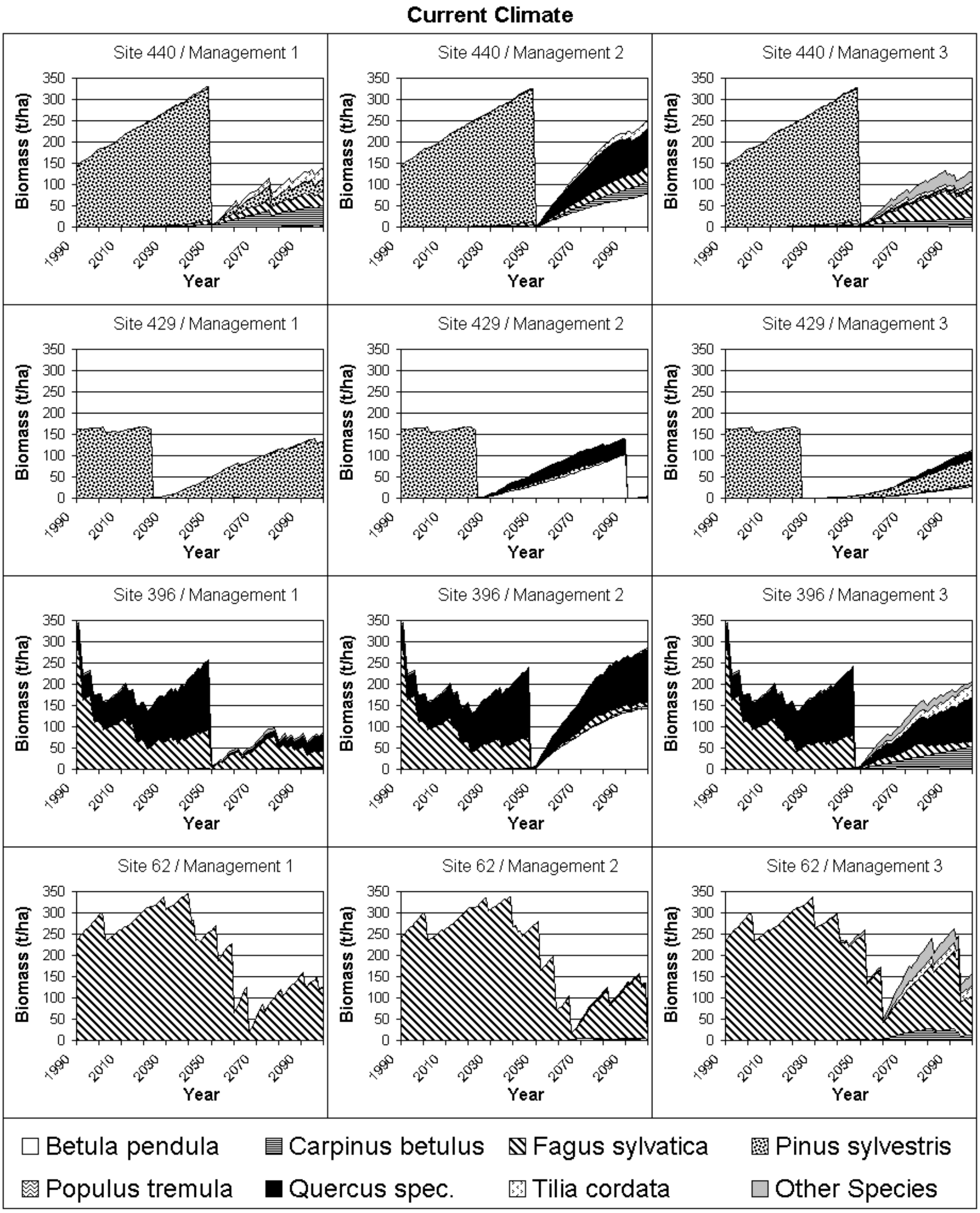

Fig. 2. Simulated transient forest development at four selected sites under current climate. The simulations were initialised with forest inventory data and run for 110 years from 1990 to 2100. The graphs show the cumulative biomass of the dominant species as averages from 10 replications. Management 1 - traditional management, Management 2 - climate adaptation, Management 3 - maximised species diversity.

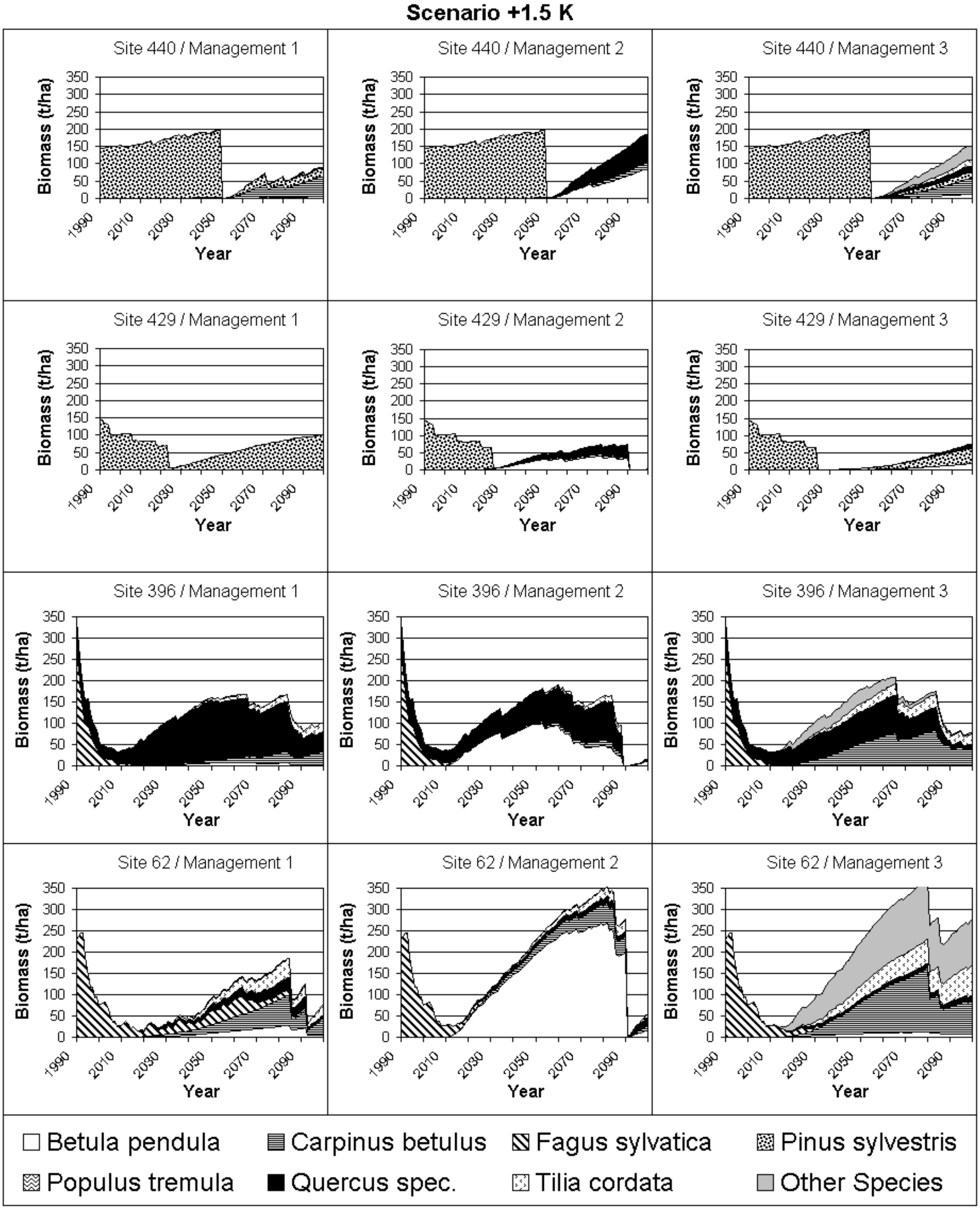

Fig. 3. Simulated transient forest development at four selected sites under a climate change scenario which is 1.5 K warmer than current climate. The simulations were initialised with the same forest inventory data as in Fig. 2 and run for 110 years. The graphs show the cumulative biomass of the dominant species as averages from 10 replications. Management 1 - traditional management, Management 2 - climate adaptation, Management 3 - maximised species diversity.

3.2 Shifting Tree Species Composition at the Regional Scale

Table 1 shows the frequency of forest types which resulted from the simulation experiment using the 488 forest inventory plots under different climate and management scenarios. There was a distinct difference between the alternative management scenarios under both climate scenarios. Whereas under traditional management (management scenario 1) pine dominated forests were still prevailing in the year 2100, the management scenarios 2 and 3 lead to an increased share of deciduous species, with a higher share of birch dominated stands in scenario P2 and a dominance of oak and hardwoods in scenario P3.

Under the changing climate there was a shift in simulated species composition towards more drought tolerant species. The share of beech, which played a minor role in all management scenarios under current climate, was diminishing. Under traditional management pine dominated forests became more dominant, whereas the adaptive and species diversity scenarios simulated a stronger dominance of oak and oak-pine forest types.

4 Discussion

Decision making in managed forests of Central Europe often has long-lasting consequences, because rotation periods are long, and a change of the species composition in a growing forest is difficult and expensive. Since climate change may have great impacts on forests, there is a strong demand for reliable recommendations, how to adapt forest management to mitigate adverse effects of the projected climate changes. However, it is currently not possible to make reliable forecasts of the regional climate within the next decades. Moreover, forest simulation models also include uncertainties and have clear limitations. This raises the question, what can be recommended to practical forestry, and what kind of information climate impact research can provide to support decision making in forest management.

The investigations presented in this paper and elsewhere (Kellomäki and Kolström 1993, Lasch et al. 1999, Lindner 2000) improve our understanding of the sensitivity of managed forests to climate change. Because the response of the forests depends on many site related factors, it is not possible to come to general conclusions. Therefore sensitivity analyses are needed for many different regions and site-specific conditions. Moreover, in order to evaluate the scenario projections it is very important to know how reliable the applied simulation models are. Although there has been considerable progress in the development of forest gap models recently (Bugmann 1996, Bugmann et al. 1996, Pacala et al. 1996, Bugmann et al. 1997, Lindner et al. 1997b, Bugmann and Cramer 1998, Lindner 2000), the complexity of the models make them difficult to validate (see also Mäkelä et al. 2000).

The FORSKA-M model has been tested under a large variety of environmental conditions from boreal (Leemans 1991, Prentice et al. 1993, Price and Apps 1996) to tropical forest ecosystems (Desanker and Prentice 1994) and its simulated potential natural vegetation (PNV) has been compared to PNV maps compiled from vegetation analysis (Lasch et al. 1999). A similar version of the model applied in this investigation has also been tested with long-term forest measurements of thinning trials with the four main forest species of Germany, Norway spruce (*Picea abies* L.), Scots pine, beech, and oak. In these model tests stand characteristics such as basal area, average height and diameter were satisfactorily represented both in weakly and heavily thinned stands (Lindner 1998). Therefore the general behaviour of the model is well understood and the simulation of species viability as well as the competitive relationships between the different species generally show plausible results. However, the experience in running the model with different management routines is still limited. The generation of variables for individual trees from stand inventory data does also include some uncertainties because some state variables of the model, e.g. the leaf area of the tree, are difficult to estimate.

The transient simulation results under current climate indicated that the model underestimated stand productivity. Especially in stands with very high initial basal area growth patterns were simulated which seem to be not plausible. Furthermore, the simulation results of management scenario 2 and 3 at site 62 with climatic change were unexpected. With decreased competitiveness of beech in the drier climate, an increasing stand productivity was simulated. Whereas the decline of beech is not surprising at this site close to the present distribution limit of beech, the fact that birch, hornbeam, sycamore and lime were simulated to be significantly more productive than beech under current climate suggests that the parameter values of the growth functions of these species need further refinements. Therefore the interpretation of results concerning the biomass production of managed forests should be carried out very carefully.

The unrealistic growth of some forest stands can be explained with an incorrect assignment of site characteristics to the inventory data. The spatial resolution of the applied digital soil map is relatively low and the spatial heterogeneity of site characteristics can be quite high in the study area. The stand characteristics of the inventory data at site 440 indicate that site quality at this site should be very low. The soil information in the GIS, in the contrary, suggests that the soil is very fertile. This explains the unexpectedly fast growth of the forest stand as well as the high competitiveness of nitrogen demanding species at this site. The opposite case, an underestimation of site quality is probably the reason for the initial drop of stand biomass on site 396, which is also accompanied by a slightly increasing competitiveness of oak. Consequently, transient simulation runs with individual forest stands should only be carried out at locations where suitable site information is available. However, erroneous site characteristics affect primarily the simulated productivity of the stands, whereas the classification into broad forest types is less sensitive to the accurate soil description. Furthermore, the error in estimating regional forest development under climate change can also be reduced by increasing the number of simulated patches, because some of the errors will equal out when larger numbers of sites are analysed. Therefore it is relatively safe to interprete aggregated regional results such as presented in Table 1.

Further efforts will be made to improve the parameterisation of the management and initialisation routines and the updated model should be applicable not only for basic research but also as a tool for forest planning, in order to support decision making in forest management under global change. Present-day forests will most likely experience altered climatic conditions within their lifetimes. There are several possibilities how forest management could respond to the prevailing risks and uncertainties. Each decision implies different consequences for the forests and the forest enterprise in the future. We propose to apply the FORSKA-M model to analyse different management strategies and their consequences. In the following, three extreme strategies are outlined and the associated risks are described.

1. Do nothing
   This strategy is adopted by a forester who does not believe in any projections of climate change and therefore the same management as in the past will be applied. Depending on local site conditions this leads to a situation, where in the year 2050 species composition of large areas of forests may be poorly adapted to the prevailing climatic conditions *if our climate is changing according to the projections of climate modellers*.
2. Prepare for worst case
   From a set of different climate change scenarios, the scenario which has the strongest effect on simulated forest growth and composition is selected. Strategy 2 than favours those species which are best adapted to this extreme climate scenario. Since e.g. drought tolerant species often are less productive than other species under good site conditions, this could lead to avoidable production losses *if the climate is changing less drastically as projected in the extreme scenario*.
3. Risk reduction strategy
   Strategy 3 tries to capture the uncertainties about our future climate. It tries to increase the species diversity both in individual forest stands and at the regional scale, thus improving flexibility and adaptive potential of forest management.

Whereas forest management strategies 1 and 2 are suitable only for certain environmental conditions, the strategy 3 will probably enable the mitigation of effects of different environmental changes without a drastic shift of present day species composition and without avoidable losses in yield. The management and climate scenarios applied in this paper were meant to examplify the general principle of analysing alternative management strategies under climatic change. In more reliable applications it will be neccessary to analyse a larger set of climate scenarios with different assumptions about the changes in temperature and precipitation. Furthermore, additional management strategies should be devised and analysed. It is quite obvious that the results of alternative management strategies will depend on the projected climate change scenario.

The extended forest gap model FORSKA-M projects the effects of alternative management strategies in terms of species composition and biomass growth. Sensitivity and scenario analyses can be used to evaluate likely consequences of changes in climate and management for timber production and timber assortments at least as qualitative trends. For example, model applications in a forest district in north-eastern Germany indicated that the adaptive management was able to partly mitigate the drop in productivity which was simulated under a traditional management and a +3K climate change scenario (Lindner 1999). In the ongoing project "German Forest Sector under Global Change" the simulated forest dynamics are linked with the stand simulator SILVA (Kahn and Pretzsch 1997) and economic models to estimate also monetary consequences of the projected climate change.

It should be kept in mind that gap models were not designed to reproduce forest stand growth at specific locations realistically. The extensions that have been introduced to the FORSKA-M model make new model applications possible. However, the focus of the analysis should not lie on the simulation of stand productivity. For this purpose, empirical forest stand simulators with environmental response functions (e.g. Pretzsch and Kahn 1996) or process-based forest gap models with detailed simulation of photosynthesis and NPP (Bugmann et al. 1997) are more suitable. The strength of the current version of the FORSKA model is the analysis of competitive relationships between species and the viability of species under changing environmental conditions. It can be applied to investigate options for forest management under global change. In future applications it is planned to apply the model at the scale of a forest enterprise, where additionally to the sensitivity analyses the economic consequences of different management choices shall be estimated and the risk of alternative strategies under different climate scenarios will be analysed.

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