Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (INIA)
Available online at www.inia.es/forestsystems
doi: http://dx.doi.org/10.5424/fs/20112003-11073

Forest Systems 2011 20(3), 453-463
ISSN: 1131-7965
eISSN: 2171-9845

Management of mixed oak-pine forests under climate scenario uncertainty

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Abstract

The process-based forest growth model 4C (FORESEE - FOREST Ecosystems in a Changing Environment) was used to analyze the growth of a mixed oak-pine stand [*Quercus petraea* (Mattuschka) Liebl., *Pinus sylvestris* L.]. The oak-pine stand is typical for the ongoing forest transformation in the north-eastern lowlands. The pine and the oak trees are 104 and 9 years old, respectively. Three different management scenarios (A, B, C) with different thinning grades and a thinning interval of five years were simulated. Every management scenario was simulated under three different climate scenarios (0K, 2K, 3K) compiled by the regional statistical climate model STAR 2.0 (PIK). For each climate scenario 100 different realisations were generated. The realisations of the climate scenarios encompass the period 2036-2060 and exhibit an increase of mean annual temperature of zero, two and three Kelvin until 2060, respectively. We selected 9 model outputs concerning biomass, growth and harvest which were aggregated to a single total performance index (TPI). The TPI was used to assess the management scenarios with regard to three management objectives (carbon sequestration, intermediate, timber yield) under climate change until 2060.

We found out that management scenario A led to the highest TPI concerning the carbon sequestration objective and management scenario C performed best concerning the two other objectives. The analysis of variance in the growth related model outputs showed an increase of climate uncertainty with increasing climate warming. Interestingly, the increase of climate induced uncertainty is much higher from 2 to 3 K than from 0 to 2 K.

Key words: mixed oak-pine stand; forest growth model 4C; climate change; uncertainty; management; multi-criteria evaluation.

Resumen

Gestión de bosques mixtos de pino y roble en escenarios de incertidumbre climática

Se ha utilizado un modelo forestal basado en procesos denominado 4C (FORESEE - FOREST Ecosystems in a Changing Environment) para analizar el crecimiento de un masa forestal con mezcla de *Quercus petraea* y *Pinus sylvestris*. Ésta es una mezcla típica en las áreas de transformación forestal en las zonas bajas del noreste de Alemania. Los pinos y los robles tienen una edad de 104 y 9 años respectivamente. Se simularon tres escenarios diferentes de manejo (A, B, C) con diferentes grados de claras e intervalos de clara de 5 años. Cada escenario de manejo fue simulado bajo tres escenarios climáticos (0K, 2K, 3K) los cuales se calcularon por el modelo regional climático estadístico STAR 2.0 (PIK). Se generaron 100 diferentes realizaciones para cada escenario climático. Las realizaciones incluyen el período 2036-2060 y presentan un aumento de la temperatura anual de cero, dos y tres grados Kelvin hasta el año 2060, respectivamente. Seleccionamos 9 salidas del modelo relacionadas con la biomasa, crecimiento y rendimiento que se combinaron en un único índice de rendimiento total (TPI, *total performance index*). El TPI fue analizado para investigar los escenarios de manejo con respecto a tres objetivos de manejo (secuestro de carbono, máximo rendimiento maderero, y un escenario intermedio a ambos) bajo la influencia de cambio climático hasta el año 2060.

Nuestros resultados indican que el escenario A muestra el TPI más alto con respecto al secuestro de carbono, y el escenario C tuvo el mejor resultado respecto a los otros dos objetivos. El análisis de varianza en las salidas relativas al crecimiento mostró que mientras más evoluciona el calentamiento global, más crece la incertidumbre climática. Cabe destacar que el aumento de la incertidumbre inducida por el clima es mucho mayor al aumentar de 2 a 3 K que de 0 a 2 K.

Palabras clave: mezcla de robles y pinos; modelo de crecimiento forestal 4C; cambio climático; incertidumbre; manejo; evaluación multi-criterio.

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Received: 29-11-10. Accepted: 20-09-11.

Introduction

Pure pine stands dominate the forest of the north-eastern lowlands in Germany. Similarly to recent forest conversion trends in other parts of Europe (Zerbe 2002), they are converted into mixed stands. One main problem in the analysis and planning of forest management in mixed stands stems from the lack of knowledge about the future climatic development. Therefore, recent studies established conceptual frameworks to evaluate forest management strategies under climate change (Prato, 2008a,b; Seidl *et al.,* 2010). They highlight the importance of considering potential risks and uncertainties from changing environmental conditions as a basis for forest management strategies. Prato (2008b) defines four steps in his framework for assessing ecosystem impacts of climate change: (1) determining the acceptability of the current state of the ecosystem; (2) specifying climate change scenarios; (3) assessing the ecosystem impacts of the scenarios; and (4) identifying the best adaptation strategies for alleviating unacceptable impacts of the climate change scenarios.

In this study the proposed framework was applied at the stand level for multiple reasons: forest managers have to deal not only with conversion from pure pine forests into mixed forests but also with a shift of the management objectives from timber production to a multifunctional sustainable forest management. Oftentimes, the questions are how silvicultural concepts modify the adaptive capacity of mixed stands to climate change (Reyer *et al.,* in press) and how to meet the objectives of several stakeholder groups. Carbon sequestration in living tree biomass and high biodiversity at tree species level are in contrast to high diameter increments of tree individuals and short rotation periods for maximizing timber yields. The changing environmental conditions may alter management objectives within one cycle of stand development or even less and are very difficult to predict. In recent years, an increase in demand of woody biomass has been observed and is likely to even increase in the future due to energy policies (Bundestag, 2004; CEC, 2007). Mixed oak-pine forests therefore also have to meet a productivity objective to be an accepted silvicultural alternative to high productive pure pine forest stands.

With this background, the obvious advantage of the proposed framework is its possibility to include the uncertainty of climate change scenarios and different management objectives. In addition, it uses various methods such as the stochastic dominance criterion to rank different management strategies depending on their ability to meet management objectives. The framework can easily be applied for a model-based assessment of management scenarios under climate uncertainty at a single forest stand: (1) determining the acceptability of the current state of the ecosystem; (2) specifying climate change scenarios; (3) model-based assessing the climate impacts of the scenarios on the forest stand; and (4) identifying the best management scenario for alleviating risks missing management objectives. Step one is not included in this study because of the general high acceptance of mixed oak-pine stands.

Scientific tools to study climate impacts on forest ecosystems are process-based forest growth models (Mäkelä *et al.,* 2000; Landsberg, 2003). We applied the forest growth model 4C to estimate frequency distribution of model output variables from different management scenarios under several climate scenarios. In this study we specify a simple example of a weighting factor times management objective matrix to evaluate the management scenarios. The output results are aggregated into a total performance index (TPI) to rank different management scenarios. We choose simple management scenarios and management objectives to better distinguish the management and climate effects at the site and to demonstrate the suitability of this method for evaluating forest management alternatives. Therefore, this study strives to answer the following questions: (1) Is the proposed framework a useful method for analyzing climate impact studies at the forest stand level? (2) What are the combined effects of management and climate scenarios on forest production?

Material and methods

The forest growth model 4C

The physiologically-based forest growth model 4C has been used to simulate growth, water, and carbon budget of trees and soils under current and projected climate and to analyze the long-term growth behaviour of forest stands with different tree species. It was applied in different studies and validated across a wide range of forest sites (Bugmann *et al.,* 1997; Lasch *et al.,* 2002, 2005). It describes processes based on ecophysiological experiments, long term studies of stand development, and physiological modelling (Haxeltine and Prentice, 1996) on tree and stand level. The model simulates tree species composition, forest structure, leaf area index as well as ecosystem carbon and water balances. The length of the growing season is provided by a species-specific phenological model with prohibitors and inhibitors by Schaber and Badeck (2003). The photosynthesis submodel is based on the photosynthesis model of Haxeltine and Prentice (1996). The model is described under the assumption of abundant water and nutrient supply. Reductions of photosynthesis by water will be considered by a drought reduction factor calculated as the ratio between soil water supply and tree water demand. For simulating water and carbon balances in the forest soil, a multilayered soil model is implemented in 4C. Water balances are calculated using a bucket model approach (Glugla, 1969; Koitzsch, 1977). The calculation of the soil temperature of every soil layer is described by Grote and Suckow (1998).

Forest stand and site

We used the process-based forest growth model 4C to analyze the growth of a mixed oak-pine stand [*Quercus petraea* (Mattuschka) Liebl., *Pinus sylvestris* L.]. The oak-pine stand is a typical example of the ongoing forest transformation on forest sites in the north-eastern lowlands where conditions for beech (*Fagus sylvatica* L.) are not suitable. It is situated in the Federal state of Brandenburg circa 80 km in the south of Berlin (Fig. 1) and is located in the transition zone between the oceanic climate of Western Europe and the continental climate of Eastern Europe. The climate in this region is one of the driest within Germany (Table 1).

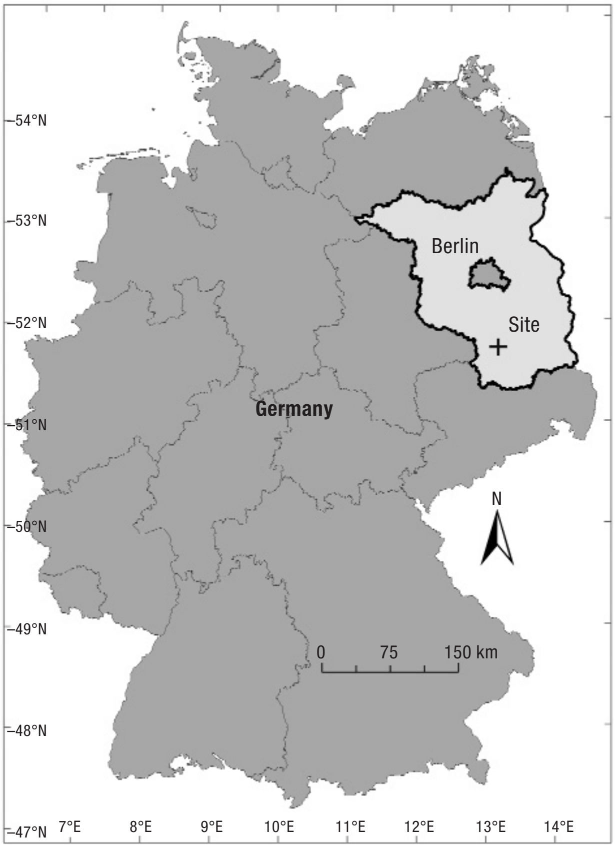

Figure 1. Location of the simulated mixed oak-pine stand in Brandenburg.

The relief is mainly even und shows only small differences in altitude. The soil characteristics are the result of fluvial and aeolian sedimentation during periglacial processes in the Pleistocene. The stand stocks on a sandy cambisol without access to groundwater. The nutrition level and the water storage capacity are low (Table 1). In the formerly pure pine forest the oak trees were planted with a density of 4,000 seedling per

Table 1. Forest site characteristics with mean annual temperature (T) and precipitation sum (P) for the period 1961-1990 (in brackets mean values for entire Germany), C/N carbon-nitrogen ratio, pH-value, base saturation (BS), plant available soil water storage capacity (FC_{paw}), age of oak and pine trees, mean diameter at breast height (d_{bh}), mean height (h_{mean}) and stem number per hectare (N_{stem})

	Climate			Soil					Stand			
	T (°C)	P (mm)		C/N	pH (H_2O)	BS (%)	FC_{paw} (mm)		Age	d_{bh} (cm)	h_{mean} (m)	N_{stem} (ha^{-1})
Year	8.3 (8.3)	589 (771)	Oh (3.8 cm)	23	4.1	42.9	—	Pine	104	33.5	26.1	386
May-September	15.2 (14.9)	291 (355)	Ah (12 cm)	27	3.9	9.6 (< 3m)	246	Oak	9	—	1.3	4,000

hectare. The stand data were measured in 2006 and were used for the initialization of the simulated stand (Table 1).

Climate scenarios

Climate scenarios enable the analysis of future development of climate conditions and its consideration in forest management planning. In this study we used climate scenarios of the regional statistical climate model STAR 2.0 (Orlowsky *et al.,* 2008). It was developed to calculate future daily weather data from observed weather time series on the base of an assumed temperature trend. Statistical methods combine observed daily weather from the past to new time series which meet the predetermined temperature trend at the end of the simulation period. The fundamental assumption of this modelling technique is that physical boundary conditions do not change during the simulation period until 2060. The climate scenarios are named after their temperature trend (0K, 2K and 3K). One climate scenario includes 100 realisations of such predetermined temperature trend. The realisations of one scenario feature the same temperature trend but the combination of the observed daily weather is different. Accordingly, they show small variation in the mean annual temperature value (Fig. 2). However, they differ in their daily values and also in their mean annual values of weather variables like precipitation and total radiation (Fig. 2). On the base of these 100 realisations per scenario it is possible to establish frequency distributions of weather variables which express uncertainty within each climate scenario.

The temperature trend of the 2 K scenario of STAR extended to the year 2100 would lead to a 3.5 K temperature increase. This is close to the 3K increase of the IPCC temperature projections for Germany for the A1B SRES scenario (Christensen *et al.,* 2007).

Management scenarios

To account for different management types, three management scenarios (A, B, C) were developed which enables testing the impacts of different thinning grades and consequently stand densities on species-specific tree growth. The thinning interval of five years was held constant over the management scenarios. The thinning intensity increases from management scenario A to management scenario C (Table 2). In case of the oak trees the thinning started after the trees reached an age of 20 years.

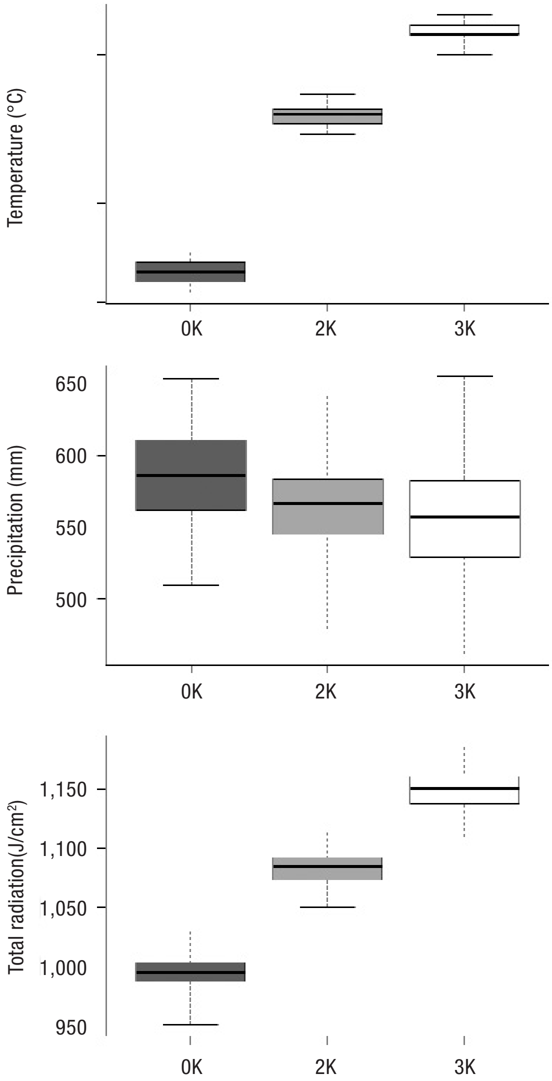

Figure 2. Box plots of different climate variables for the three climate scenarios (0K, 2K, 3K) of the period 2036-2060 at the investigated forest site. The thick black line denotes the median, the boxes indicate 25 and 75-percentiles, and the Whiskers show sample minimum or sample maximum.

Model simulations

The model 4C was run for the mixed oak-pine stand under the three different management scenarios and for three different climate change scenarios and their respective realisations as described above. The combination of climate scenarios and management scenarios

Table 2. Forest management scenarios used in the analysis with different thinning grades. Numbers represent remaining stems per hectare

Year	A		B		C	
	Pine	Oak	Pine	Oak	Pine	Oak
1	207	—	156	—	117	—
6	192	—	144	—	108	—
11	179	3,543	134	3,468	101	3,393
16	168	3,325	126	3,183	94	3,041
21	159	3,115	118	2,913	88	2,711

Table 3. Definition of simulation experiment runs

Climate scenario/ management scenario	A	B	C
0K	A-0K	B-0K	C-0K
2K	A-2K	B-2K	C-2K
3K	A-3K	B-3K	C-3K

is described in Table 3. The simulation period covered 25 years from 2036-2060. The simulated output of the stem increment of the total stand was taken to distinguish between climate realisation effects and management effects within a climate scenario. For this reason a bifactorial analysis of variance were performed with the three management scenarios and the 100 climate realisation of one climate scenario.

Multi-criteria evaluation concept

To evaluate the management scenarios under climate change, we used the total performance index (TPI) according to (Prato 2008b). We selected nine model output variables (Table 4) as impact criteria.

Furthermore, we considered the following management objectives:

— Objective 1: maximizing carbon sequestration on the site (O1).

— Objective 2: an intermediate objective between objective 1 and objective 3 with moderate focus on growth (O2).

— Objective 3: maximizing yield and carbon sequestration in forest products (O3).

We defined exemplary weighting factors between 1 and 4 for these management objectives for each output variable according to their different foci to calculate the TPI (Table 4).

The TPI aggregates the normalised output variables of the model and is calculated in the following way:

1) Calculation of the maximum $X_{\max, j,i,}$ (j = 1,…,9, i = A, B, C) for each output variable and each management scenario from the set $X_{j,i} = \{x_{j,i}^{k}, k = 1,\ldots, 100\}$ of 100 values $x_{j,i}^{k}$ resulting from 100 simulation runs.

2) Calculation of maximum values over the three management scenarios:

$$X_{\max, j} = \text{maximum}(X_{\max, j,i,}), \text{ for } i = A, B, C$$

3) Calculation of a set of normalised values $X_{j,i}^{n}$ for output variable j (j = 1,.., 9) and management i (i = A, B, C):

$$X_{j,i}^{n} = \frac{X_{j,i}}{X_{\max, j}}$$

4) Calculation of the TPI for each management scenario i (i = A, B, C) as weighted average:

$$TPI_i = \frac{\sum_{j=1}^{9} w_j X_{j,i}^{n}}{\sum_{j=1}^{9} w_j}$$

The values of TPI_i (i = A, B, C) were calculated for each of the three climate scenarios. A triangular probability distribution was established with minimum, median and maximum of each set of TPI values from which the cumulative distribution function (CDF) was

Table 4. Weighting factors for three different management objectives

Management objetive	w_1 Biomass*	w_2 Growth*	w_3 Harvest*	w_4 Biomass Pine	w_5 Growth Pine	w_6 Harvest Pine	w_7 Biomass Oak	w_8 Growth Oak	w_9 Harvest Oak
Objective1 (O1)	4	4	1	4	4	1	3	3	1
Objective2 (O2)	1	2	1	1	2	1	1	3	1
Objective3 (O3)	1	1	4	1	1	4	1	1	4

* Biomass: above and belowground biomass at the end of the simulation period (t DW ha^{-1}). Growth: sum of annual stem mass increment (t DW ha^{-1}). Harvest: sum of harvested stem wood (t DW ha^{-1}).

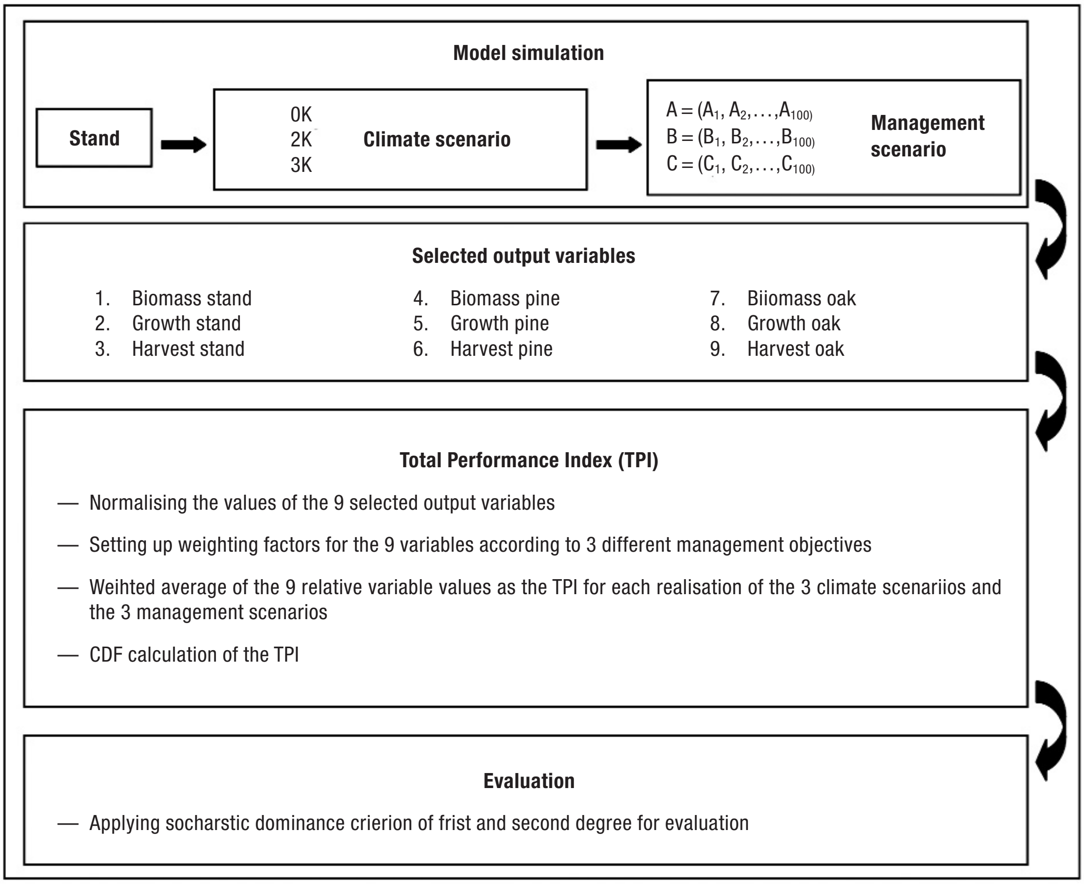

Figure 3. Overview of the methodological approach used in this study.

derived. Using the method of stochastic dominance (Schmid and Trede, 2006) these values were analysed for each management objective, climate, and management scenario. The stochastic dominance is defined as follows: if the value of the CDF of an option B, $F_B(x)$, is less or equal than the value of CDF of an option A, $F_A(x)$, for each value of x, then is option B stochastic dominant of first degree.

Figure 3 sums up the applied methods and the progression of the working steps.

Results and discussion

Simulations

Biomass

The total biomass for one management scenario after 25 simulation years is highest under the 0K scenario, slightly lower under the 2K scenario and lowest under the 3K scenario (Fig. 4). Much stronger differences in total biomass occur between the management scenarios within each scenario (Fig. 4). Management scenario A always yields the highest total biomass (around 450 t DW ha^{-1}), management scenario B yields around 370 t DW ha^{-1}, and management scenario C always ends up with around 310 t DW ha^{-1}.

The total biomass at the end of the simulation period heavily depends on the stand growth and on the harvest level during the simulation. The decreasing total biomass from management scenario A to C thus reflects increasing management intensity in these scenarios. This is in accordance with results from modeling and experimental studies (Skovsgaard *et al.,* 2006). Although, the effect of the climate scenarios on the total biomass is much less pronounced than the effect of the individual management scenarios, there is still a decreasing trend in total biomass from the 0K to the 3K scenario visible. A warmer climate decreases total biomass in all three management scenarios; however, this variation between climate scenarios is much smaller than the va-

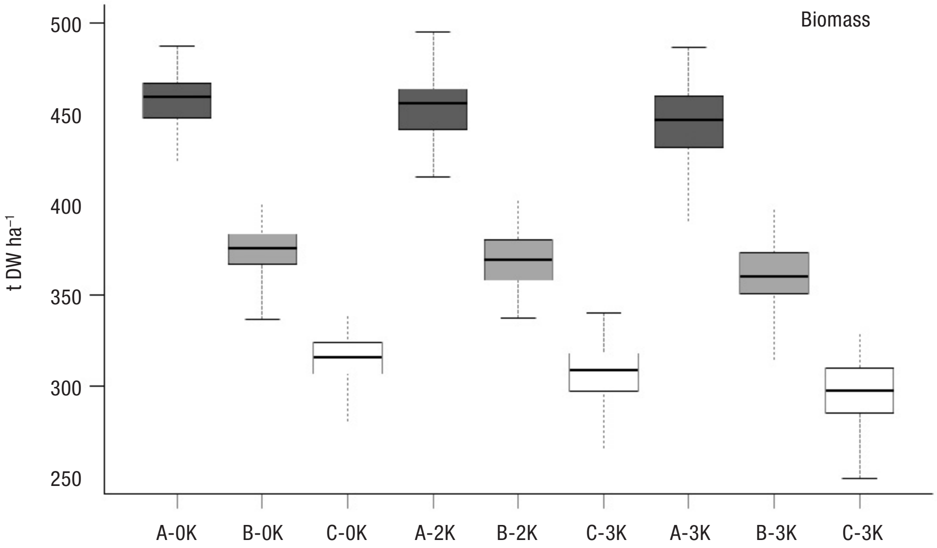

Figure 4. Final Biomass for three management scenarios and three climate scenarios. The thick black line denotes the median, the boxes indicate 25 and 75-percentiles, and the Whiskers show sample minimum or sample maximum.

riation between management scenarios. This confirms recent climate impact studies which find a much stronger effect of management-related issues such as cutting cycle, age structure of the forest or management history than of climate change in managed European forests (Lindner, 2000).

Growth and harvest

The results for stem mass increment show a similar pattern than the total biomass. Across the climate scenarios, increasing management intensity features decreasing stem increment as a consequence of the higher harvest rates and a warmer climate induces lower growth across management scenarios (Fig. 5).

When considering the harvested stem wood, the pattern among the management scenarios is inversed. With increasing management intensity, the amount of harvested wood logically increases too (Fig. 5). However, the amount of harvested stem wood varies only very little in between the different climate change scenarios and the variation around the median is much smaller than for total biomass and biomass growth (Fig. 5). Thus, the amount of harvested stem wood is almost independent of the climate.

Allocating carbon to the stem comes at the lower end of the allocation hierarchy in trees (Waring, 1987) and results in lower stem mass increment in years with less favourable conditions. The diameter at breast height is positively correlated with total biomass (Lehtonen *et al.,* 2004) and also with the competiveness of a tree. Furthermore trees with high growth rates have better access to water and radiation. Since we simulated thinning from above the highest and more competitive tree individuals were harvested first. Hence, trees with less growth variation in the past come to the harvest pool and trees with higher growth variation remain on the site. This explains why the total biomass and growth is more sensitive to changes in climate than the yield.

Effects of management and climate within the climate scenario

To detect the relative contribution of management and climate over 100 realisations to the uncertainty of the simulated stem mass increment within the different climate change scenarios, we calculated the coefficient of variation of management and climate. The warmer climate change scenarios induce a higher coefficient of variation for both climate and management (Fig. 6). For the 0K and 2K scenarios, the influence of the climate is lower than the influence of the management but under the 3K scenario the coefficient of variation of the climate is clearly higher than the management one (Fig. 6). The increase in influence of the management across the three climate change scenarios is almost linear, whereas the influence of the clima-

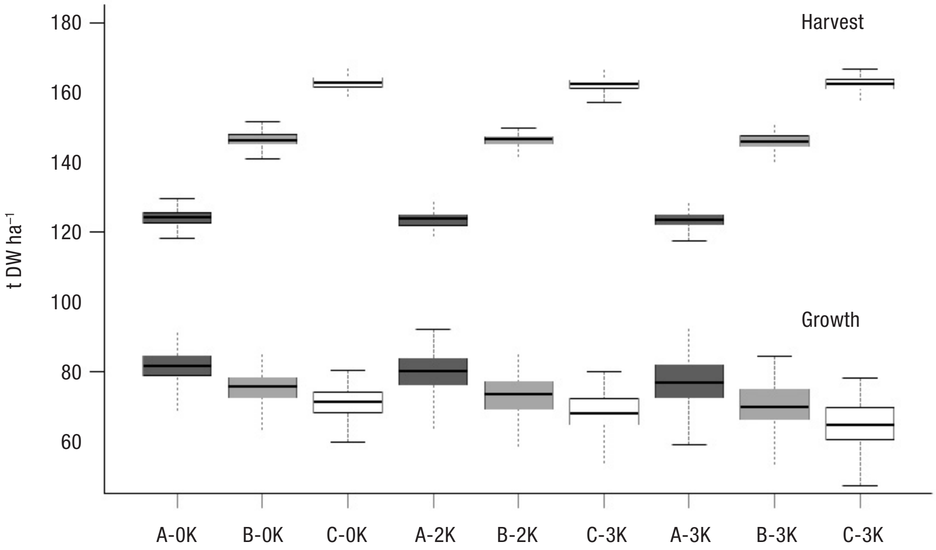

Figure 5. Sum of harvested stem wood (above the dotted line) and sum of stem mass increment (below the dotted line) for three management scenarios and three climate scenarios. The thick black line denotes the median, the boxes indicate 25 and 75-percentiles, and the Whiskers show sample minimum or sample maximum.

te undergoes a steep increase from the 2K to the 3K scenario.

Additionally, to the coefficient of variation, we performed a bivariate analysis of variance to track the degree to which the overall variance of stem mass increment can be attributed to the influence of the climate (as expressed by 100 realisations) and of management in the model. Under the 0K scenario both climatic and management influence explain about 50% of the variance respectively (note that since management and climate were the only contributing variances in this analysis, they sum up to the total variance *i.e.* 100%). With increasing warming the influence of the climate increases and the influence of the management decreases (Fig. 7). The strongest increase (decrease for management) occurs from the 2K scenario to the 3K scenario. This is a noteworthy result because it exemplifies the non-linear dynamics of the climate impacts. Whereas a net temperature increase of 2K from the 0K scenario to the 2K scenario induces only slight changes in the variance explained by the 100 realisations, a further net increase by only 1K from the 2K scenario to the 3K scenario adds about 5% to this variance.

The analysis of the coefficients of variation and the analysis of variance show that the climatic uncertainty increases under higher temperatures and its in-

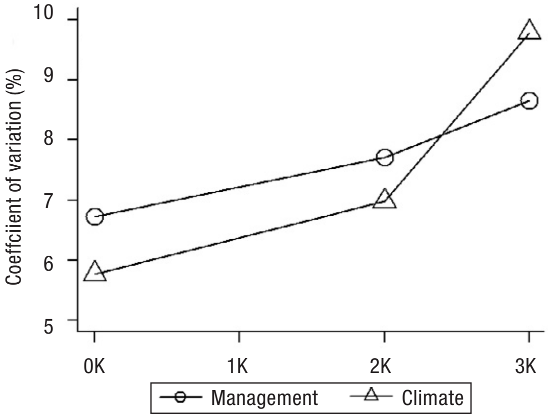

Figure 6. Coefficient of variation for the simulated stem mass increment.

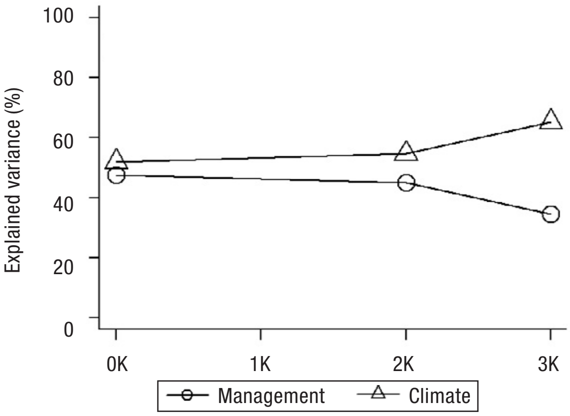

Figure 7. Explained variance for the simulated stem mass increment.

fluence may become more important than the management influence in the future. This is especially important since we only simulated stem mass increment without accounting for changes in disturbances such as storms or insects, which are likely to increase (Panferov *et al.,* 2009; Lindner *et al.,* 2010) and have the potential to increase the influence of the climate dramatically.

Multi-criteria evaluation

The set of weighting factors and management objectives only serve as a simple example to test the methodological approach. In practice a climate impact study who aims analyzing adaptation capacities or adaptation strategies need the participation of stakeholder groups (Prato, 2008b. Seidl *et al.,* 2010).

For the first objective, management scenario A has the highest probability of reaching a high total performance index across all climate change scenarios (Fig. 8). This coincides with the low thinning grade which led to high biomasses of the old pine. The high weighting factors assigned to biomass in objective 1 (Table 4) supports the TPI of management scenario A. Thus, management scenario A is most suitable for achieving objective 1. For the second and the third objective, management scenario C is most probable to achieve the highest TPI (Fig. 8).

Similarly to the relationship of objective 1 and management scenario A, the results for the third objective coincide with a focus on harvest in management scenario C and high weights for harvest in objective C. Thus, this confirms the expectations that a management scenario C would be most suitable for objective 3. The results for objective 2 deserve closer attention,

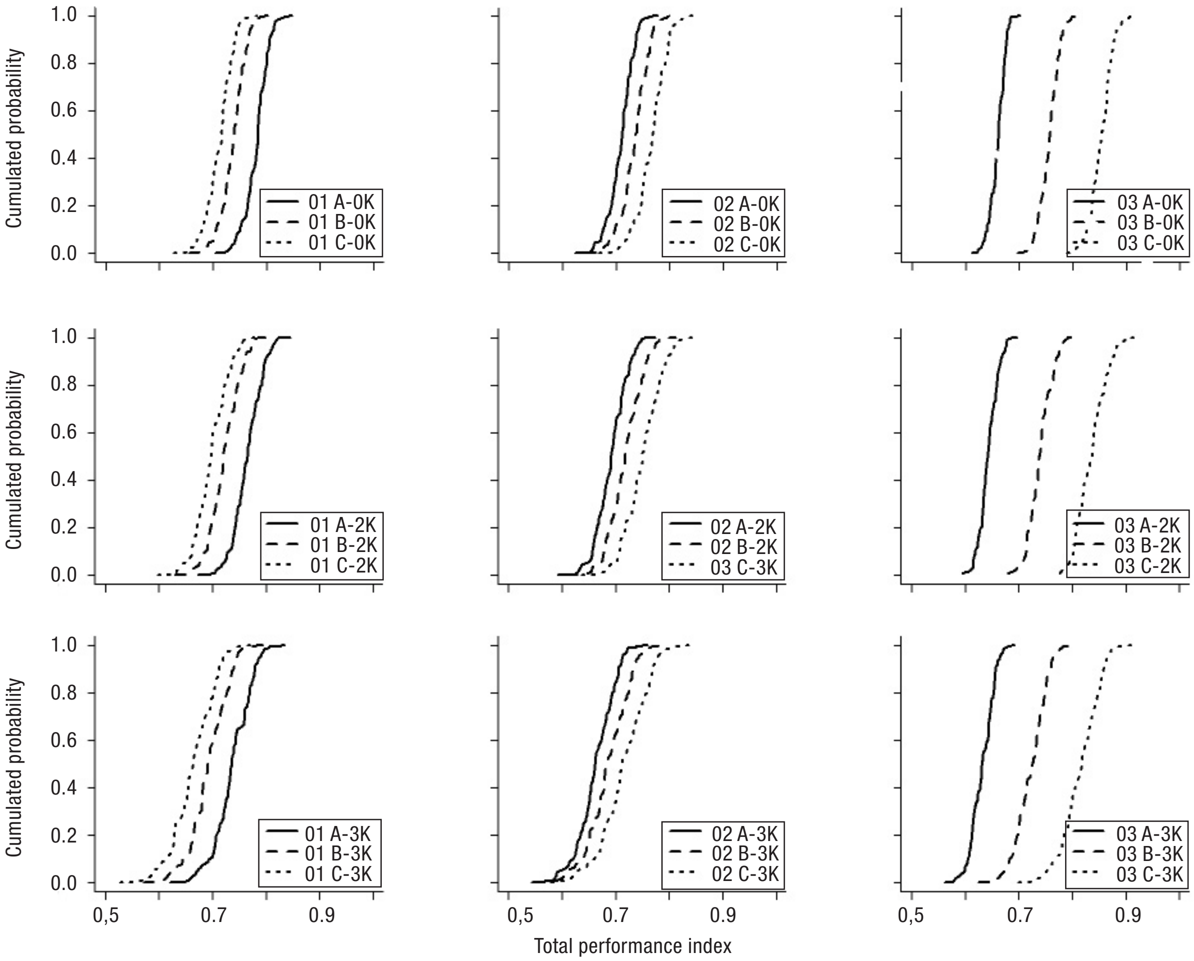

Figure 8. Cumulated probability distribution function of the TPI for three management scenarios (A, B, C), for the three climate scenarios (0K, 2K, 3K) and for three sets of weighting factors for the management objectives (O1, O2, O3).

since this objective balances harvest on the one hand and total biomass and growth on the other hand. Biomass and harvest are not pronounced by the weighting factors, only growth of oak, pine and the total stand are higher weighted. This objective is most likely attained with the strongest management scenario indicating that the losses in total biomass and growth as suggested by the simulation results (Fig. 4; Fig. 5) in this scenario are compensated by the much higher harvest levels (Fig. 5). Furthermore, the lower uncertainty of harvest levels (see section *Growth and Harvest*) within the 100 realisations explains why management scenario C also performs best for objective 2. Additionally, the low stock of old pine trees in management scenario C have positive effects on the growth of young oak trees which is amplified by the weighting factors.

Concerning the shape of the CDFs it can be stated that the slope of the CDF is less steep with higher temperature trend which reflects the higher variation (see in section *Effects of management and climate within the climate scenario*). This leads to lower probability reaching a certain level of TPI but does not change the ranking of management scenarios in this study.

Conclusion

The conceptual framework developed within this study — the integration of climate and management scenarios, taking into account climate uncertainty and management objectives, and the development of a performance index— is a unique approach in forest sciences. The focus on mixed stands has rarely been investigated; therefore this study is of great importance for foresters. The approach has proven to be highly suitable for the assessment of climate impacts on forest stands.

The analysis of variance of growth related model outputs and the CDFs of the TPI showed an increase of climate uncertainty with increasing climate warming. Interestingly, the increase of climate induced uncertainty is much higher from 2 to 3 K than from 0 to 2 K. This exemplifies the non-linear impacts of climate change on forest growth.

For future applications of this framework in forest management and forest decision making it is necessary to determine the weighting factors more precisely by involving stakeholders and forest experts.

Acknowledgment

This study was partly funded by the BMBF project «OakChain» with the reference number 330576E.

References

BUGMANN H., GROTE R., LASCH P., LINDNER M., SUCKOW F., 1997. A new forest gap model to study the effects of environmental change on forest structure and functioning. Impacts of global change of tree physiology and forest ecosystem (Mohren G.M.J., Kramer K., Sabate S., eds). Proceedings of the International Conference on Impacts of Global Change on Tree Physiology and Forest Ecosystems, held 26-29 November 1996, Wageningen, Dordrecht, Kluwer Academic Publisher. pp. 255-261.

BUNDESTAG D., 2004. Gesetz für den Vorrang erneuerbarer Energien. BGBl 2004 I Nr. 40. D. Bundestag, Deutscher Bundestag. pp. 1918-1930.

CEC, 2007. Renewable energy road map renewable energies in the 21st century: building a more sustainable future. B. Brussels, Commission of the eurpean communities. COM(2006) 848.

CHRISTENSEN J.H., HEWITSON B., BUSUIOC A., CHEN A., GAO X., HELD I., JONES R., KOLLI R.K., KWON W.-T., LAPRISE R., MAGAÑA RUEDA V., MEARNS L., MENÉNDEZ C.G., RÄISÄNEN J., RINKE A., SARR A., WHETTON P., 2007. Regional climate projections. In: Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Solomon S., Qin D., Manning M., Chen Z., Marquis M., Averyt K.B., Tignor M.M., Miller H.L., eds). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

GLUGLA G., 1969. Berechnungsverfahren zur Ermittlung des aktuellen Wassergehaltes und Gravitationswasserabflusses im Boden. Albrecht-Thaer-Archiv 13, 371-376.

GROTE R., F. SUCKOW F., 1998. Integrating dynamic morphological properties into forest growth modeling. I. Effects on water balance and gas exchange. Forest Ecology and Management 112, 101-119.

HAXELTINE A., PRENTICE I.C., 1996. BIOME3: an equilibrium terrestrial biosphere model based on ecophysiological constraints, resource availability and competition among plant functional types. Global Biogeochemical Cycles 10(4), 693-709.

HAXELTINE A., PRENTICE I.C., 1996. A general model for the light-use efficiency of primary production. Functional Ecology 10(5), 551-561.

KOITZSCH R., 1977. Schätzung der Bodenfeuchte aus meteorologischen Daten, Boden- und Pflanzenparametern mit einem Mehrschichtmodell. Z f Meteor 27(5), 302-306.

LANDSBERG J.J., 2003. Modelling forest ecosystems: state of the art, challenges, and future directions. Canadian Journal of Forest Research 33(3), 385-397.

LASCH P., BADECK F.W., SUCKOW F., LINDNER M., MOHR P., 2005. Model-based analysis of management alternatives at stand and regional level in Brandenburg (Germany). Forest Ecology and Management 207(1-2), 59-74.

LASCH P., LINDNER M., ERHARD M., SUCKOW F., WENZEL A., 2002. Regional impact assessment on forest structure and functions under climate change - the Brandenburg case study. Forest Ecology and Management 162(1), 73-86.

LEHTONEN A., MAKIPAA R., HEIKKINEN J., SIEVANEN R., LISKI J., 2004. Biomass expansion factors (BEFs) for Scots pine, Norway spruce and birch according to stand age for boreal forests. Forest Ecology and Management 188(1-3), 211-224.

LINDNER M., 2000. Developing adaptive forest management strategies to cope with climate change. Tree Physiology 20(5-6), 299-307.

LINDNER M., MAROSCHEK M., NETHERER S., KREMER A., BARBATI A., GARCÍA-GONZALO J., SEIDL R., DELZON S., CORONA P., KOLSTROM M., LEXER M.J., MARCHETTI M., 2010. Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. Forest Ecology and Management 259(4), 698-709.

MÄKELÄ A., LANDSBERG J., EK A.R., BURK T.E., TER-MIKAELIAN M., AGREN G.I., OLIVER C.D., PUTTONEN P., 2000. Process-based models for forest ecosystem management: current state of the art and challenges for practical implementation. Tree Physiology 20(5-6), 289-298.

ORLOWSKY B., GERSTENGARBE F.W., WERNER P.C., 2008. A resampling scheme for regional climate simulations and its performance compared to a dynamical RCM. Theoretical And Applied Climatology 92(3-4), 209-223.

PANFEROV O., DOERING C., RAUCH E., SOGACHEV A., AHRENDS B., 2009. Feedbacks of windthrow for Norway spruce and Scots pine stands under changing climate. Environmental Research Letters 4(4).

PRATO T., 2008a. Accounting for risk and uncertainty in determining preferred strategies for adapting to future climate change. Mitigation and Adaptation Strategies for Global Change 13(1), 47.

PRATO T., 2008b. Conceptual framework for assessment and management of ecosystem impacts of climate change. Ecological Complexity 5(4), 329-338.

REYER C., LASCH P., MOHREN G.M.J., MOHREN S.F. (in press). Inter-specific competition in mixed forests of Douglas-fir (*Pseudotsuga menziesii*) and Common beech (*Fagus sylvatica*) under climate change - a model-based analysis. Annals of Forest Science.

SCHABER J., BADECK F.-W., 2003. Physiology based phenology models for forest tree species in Germany. Intern J Biometeorol 47(7), 193-201.

SCHMID F., TREDE M., 2006. Finanzmarktstatistik. Heidelberg, Springer.

SEIDL R., RAMMER W., LEXER M., 2010. Climate change vulnerability of sustainable forest management in the Eastern Alps. Climatic Change: 1.

SKOVSGAARD J.P., STUPAK I., VESTERDAL L., 2006. Distribution of biomass and carbon in even-aged stands of Norway spruce [*Picea abies* (L.) Karst.]: a case study on spacing and thinning effects in northern Denmark. Forest Research 21(6), 470-488.

WARING R.H., 1987. Characteristics of trees predisposed to die. Bioscience 37(8), 569-574.

ZERBE S., 2002. Restoration of natural broad-leaved woodland in Central Europe on sites with coniferous forest plantations. Forest Ecology and Management 167, 27-42.