

Modelling and economic evaluation of forest biome shifts under climate change in Southwest Germany

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ABSTRACT

We evaluated the economic effects of a predicted shift from Norway spruce (*Picea abies* (Karst) to European beech (*Fagus sylvatica* (L) for a forest area of 1.3 million ha in southwest Germany. The shift was modelled with a generalised linear model (GLM) by using presence/absence data from the National Forest Inventory in Baden-Württemberg, a digital elevation model, and regionalised climate parameters from the period 1970 to 2000. Two scenarios from the International Panel on Climate Change (IPCC) (B1, A2) for three different time scales (2030, 2065, and 2100) were investigated. The GLM predicted a decrease of the suitable area for growing Norway spruce between 21% (B1, 2030) and 93% (A2, 2100) in comparison to 2000. This corresponds to a reduction in the potential area of Norway spruce from between 190,000 and 860,000 ha. The financial effect of this reduction in area was then evaluated by using a classical Faustmann approach, namely the land expectation value (LEV) as an economic parameter for forests of Norway spruce versus European beech. Underlying cash flows were derived from a distance dependent, single-tree growth simulator (SILVA) based on data for prices and costs of the year 2004. With an interest rate of $r = 2\%$, the predicted loss in the potential area of Norway spruce is related to a decrease of the LEV between 690 million and 3.1 billion Euro. We discuss the sensitivity of these results to changing interest rates, risk levels, and rotation lengths. Results suggest that managing forestland for profitability will be increasingly difficult under both climate scenarios.

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1. Introduction

1.1. Background

A changing climate increases the probability of shifts in forest biomes, as tree species are subject to increasing temperatures and/or changes in water regimes. Thuiller (2007) estimated that each 1°C of temperature change moves ecological zones on Earth by about 160 km in a North-South direction. Effects on the potential distribution of (tree) species (Elith et al., 2006; Zimmermann et al., 2006) and, thus, on the future impact of disturbance regimes (Dale et al., 2001) are emphasized in the growing literature on climate change. Far less attention is given to estimating the economic consequences associated with the ecological effects of biome shifts and the policies intended to mitigate or adapt to them. It is important to understand potential economic effects, however, since they influence the viability of any proposed forest management activities.

In central Europe, active forest transformation from Norway spruce (*Picea abies*, Karst) to European beech (*Fagus sylvatica*, L.) is

already ongoing on a large scale (Spiecker et al., 2004). Although several studies deal with the differences in economic productivity between these two species, they are mostly about forest transformation (Bredahl Jacobsen et al., 2004; Mohring, 2004) or on the merits of mixed forests (e.g. Knoke et al., 2008). An economic evaluation of the expected range shifts of major European tree species, taking into account that Norway spruce will be one of the big "losers" of climate change, has not yet been done.

1.2. Choice of tree species as risk prevention

Transforming forests from species that are presumably less adapted to an expected climate change to species that may be more suitable for changing environmental conditions is a way of risk handling within a risk management process (Haimes, 2004).

The typology of risk management is well established in general business economics and in insurance mathematics (Haimes, 2004). The process generally comprises three major steps: (i) risk analysis or risk assessment (divided into risk identification and risk evaluation), (ii) risk handling and (iii) risk control. In economic theory, risky decisions have known outcomes with known

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probabilities (Bannock et al., 1979). In contrast, an uncertain decision has a known number of outcomes, but the probability of each outcome is unknown. It is of particular importance for forestry to consider risk as it relates to uncertainty because predictions always include uncertainty, which renders the consequences of decisions about changing species mixtures difficult to assess. Debate exists about the meaningfulness of distinguishing risk from uncertainty. For example, Hirshleifer and Riley (1992, p. 10) do not differentiate between them, but instead define risk as a situation in which individuals assign probabilities to events with a subjective degree of belief.

Measures of risk handling can be divided into cause-oriented or effect-oriented. Cause-oriented measures aim either at avoiding damage by abandoning risk-prone activities (risk avoidance) or at reducing the probability of damage by adopting preventive measures (risk prevention). Risk prevention includes all measures aiming at increasing the stability of forests such as early thinnings to influence the height/diameter ratio of the trees (Abetz and Kramer, 1976; Slodick and Novak, 2006), or choosing tree species that are less prone to abiotic or biotic damage on a given site. Thus, the development of bioclimatic envelopes for major tree species (Kolling, 2007) under different climate scenarios can be looked upon as a way to support practitioners in risk prevention. However, the final step in the risk management process requires understanding the costs of the activities adopted relative to how the probability of loss has changed. For this, an economic evaluation is a necessary step.

1.3. Goals of the study

We first wanted to quantify how much the potential area of Norway spruce may change due to an expected warming under different climate change scenarios. Our study area is around 1.3 million ha in Southwest Germany. Compared to average site conditions in Europe the area is of high productivity. Our next goal was to estimate the change in land expectation value (LEV) associated with shifting from managing forests of Norway spruce to those dominated by European beech. Finally, we sought to evaluate the financial consequences of shifting from Norway spruce to European beech under different climate scenarios by using the reduction in LEV as a proxy for the reduction of the value of forestland due to climate change. We tested the sensitivity of important parameters such as interest rate, rotation length and level of risk on our results.

Our specific questions were:

- (i) How does the potential area of Norway spruce in Southwest Germany change under an assumed climate change with increasing temperatures according to the IPCC scenarios B1 and A2?
- (ii) How does the LEV of Norway spruce under actual price-cost relations compare to that of European beech in the study area?
- (iii) What are the financial consequences of a climate change induced shift from Norway spruce to European beech as predicted under IPCC scenarios B1 and A2?
- (iv) What is the influence of interest rate, rotation length and different levels of risk on the economic results of the assumed shift?

2. Material and methods

2.1. Species distribution model

To estimate future biome shifts we need to predict possible future species distributions given the SRES-scenarios. We used a logistic regression (a generalised linear model with

binary response) to model the distribution of Norway spruce (Eq. (1)):

$$\log \frac{\text{Prob}(y_i = 1)}{1 - \text{Prob}(y_i = 1)} = \sum_{m=1}^p \beta_m x_{im}, \quad (1)$$

$$\text{cov}(E[Y_i] - Y_i, E[Y_j] - Y_j) = 0 \quad \forall \quad i \neq j,$$

where Y_i denotes the i -th observation and β_j is the parameter for the j -th explanatory variable, x_{ij} .

The response variable was the observation-of species presence/absence derived for each one of 13,031 sample plots of the second national forest inventory (NFI) on a total forest area of 1,323,119 ha in Baden-Württemberg (Southwest Germany). The individual observations of tree species are (conditionally) binomially distributed: $Y_i/x_i \sim \text{Binomial}(1, \pi_i)$, which, because of binary data in this case ($n = 1$), is a Bernoulli distribution.

The set of potential explanatory variables covered slope (slp25), aspect (asp25) and height above sea level (hoe25) from a 25 m x 25 m digital elevation model as topographic predictors (no other soil related variables were tested) and 11 long-time (over the period 1971 until 2000) bioclimatic variables. These variables were derived via downscaling data from a global circulation model (ECMWF ERA40, CDAS/NCEP-NCAR) using the Weather Research and Forecasting Model (WFM) and geostatistically interpolating the data at the NFI plots using local climatic measurements of the German Weather Service (DWD) as covariables (Bohner, 2005). Within the statistical downscaling, the influence of relief and surface on local climatic conditions was analysed using the System for Automated Geoscientific Analyses (SAGA) and integrated into an area-related climatological regionalisation by parameterizing a geostatistical model. The validation and calibration of the model was done using existing series of measurements of the DWD based on a local regression approach (Bohner, 2005, p. 55). The variables we used were the mean temperature of the coldest (tmcm) and warmest (tmwm) month, the annual drought index (adi), the annual sums and the sums over the growing season (May until October) of temperature (tsa and tsg), precipitation (psa and psg), potential radiation (prsa and prsg) and water balance (wfa and wfg).

To avoid multicollinearity, we subsequently dropped from the full set of predictors any variable which could be explained by using a linear combination of the remaining variables with highest R^2 until we reached $R^2 = 0.8$. This left us with a reduced set of 2 topographic and four bioclimatic predictors, namely slope [degree] (slp25), aspect (asp25) [degree], temperature of the coldest month [°C] (tmcm), temperature of the warmest month [°C] (tmwm), annual sum of precipitation over the growing season [mm] (psg) and the annual sum of radiation [J/cm²] (prsa). Mean, extrema, first, second and third quartiles of these predictor variables are listed in Table 1.

A stepwise selection based on the Bayesian information criterion (BIC) (see Schwarz, 1978) dropped tmwm and gave us the parameter estimations of the final model. The explained deviance (see McCullagh and Nelder, 1989, Chapter 2.3.1) was adjusted following an approach suggested by Guisan and Zimmermann (2000). We give the area under the receiver-operating-characteristic curve (AUC see Hanley and McNeil, 1982) as a customary measure of the precision of prediction, and we optimised the threshold for transforming the predicted probabilities into binary presence/absence predictions using Cohen's kappa (see Bishop et al., 1975). We cross-validated the model 10-fold to test its stability.

For the projection of potential future species distribution we modified the temperature values for model input by the mean global warming given for the scenarios B1 and A2 by Solomon et al. (2007, p. 763, Table 10.5).

Table 1
Moments of distributions of predictors.

	slp25	asp25	tmcm	tmwm	psg	prsa
Min	0.007277	0.00	-3.9897	11.57	328.0	10148
1st Qu.	3.383960	89.16	-1.1692	16.24	468.1	19186
Median	8.092293	176.79	-0.2398	17.09	525.9	20466
Mean	10.787210	180.01	-0.1878	17.05	558.6	20234
3rd Qu.	16.756063	274.40	0.6677	17.86	626.8	21512
Max	51.044628	360.00	2.9819	21.58	1038.3	26765

1st/3rd Qu.: 1st/3rd quartile; slp25: slope; asp25: aspect (both from a 25 m × 25 m digital elevation model); tmcm, tmwm: temperature of the coldest (tmcm) and warmest (tmwm) month; psg: the sum over the growing season (May until October) of precipitation; prsa: annual sum of potential radiation.

We distinguish five categories of biome shifts:

1. *Presence*: The species is present in the NFI data as well as in the model prediction of the potential future species distribution under the considered scenario.
2. *Absence*: The species is absent both in the NFI data and in the model prediction of the potential future species distribution under the considered scenario.
3. *Expansion*: The species was not present in the NFI data but is present in the model prediction of the potential future species distribution under the considered scenario.
4. *Reduction*: The species was present in the NFI data but is not in the model prediction of the potential future species distribution under the considered scenario.
5. *Extrapolation*: We did not calculate a model prediction for locations where at least one of the projected future climatic variables under the considered scenario was out of its current range.

We interpreted the sum of Category 1 and Category 3 as the potential future area suitable to grow Norway spruce under bioclimatic aspects for the different climate scenarios. We compared the difference of the suitable area for Norway spruce from the two scenarios to the suitable area in the year 2000, as classified by the model. We then evaluated this difference from an economic point of view, in which we assumed that on any area not still suitable for Norway spruce, growing European beech would still be possible.

2.2. Economic evaluation of biome shift from Norway spruce to European beech

2.2.1. Faustmann approach

We used the LEV (Faustmann, 1849) as a proxy for changes in the willingness to pay for forestland managed either for Norway spruce or for European beech.

The LEV can be expressed according to Klemperer (1996) as a series of discounted cash flows issued from forestland management. The formulation of the LEV we use in this paper is close to that of Dieter (2001) with:

$$\text{LEV} = \frac{Fh_t + \sum_{a=1}^{t-1} Th_a(1+i)^{t-a} - c(1+i)^t}{(1+i)^t - 1}$$

where LEV is the land expectation value, Fh_t is the net stumpage value at the end of the rotation time t , Th_a is the net revenue for thinning (young growth tending) at time a , $(1+i)$ is the discounting (interest) factor with the interest rate i and c , the cost for replanting (natural regeneration). We here used the classical Faustmann formula as appropriate for the problem under investigation. The LEV, as reflected by this formula, does not take

into account the value of the forest. This formula is consistent with how we modelled biome shifts; they do not represent the actual state of the forest, but instead reveal the potential areas of tree species.

2.2.2. Growth simulation

In order to compare the economic performance of spruce and beech we generated cash flows based on the growth simulation of model stands issued from the national forest inventory in Baden-Württemberg. For both tree species we started with a 30-year-old stand and ran simulations with the distance dependent growth simulator Silva 2.1 (Pretzsch, 2003) for 22 periods of 5 years each. We assumed equal site conditions for both model stands (dominant height for spruce = 35.7 m and for beech = 31.3 m at age 100) and species-adapted treatment programs (crop-tree-oriented high thinning) according to regional silvicultural prescriptions for Southwest Germany (MLR, 1999).

2.2.3. Prices and costs

We assumed timber prices for the year 2004 as not being influenced by large disturbances for both species based on sales statistics of the State Forest in Baden-Württemberg (FOFIS, 2005) and actual harvesting and planting costs and costs for young growth tending. For beech as a natural species in Baden-Württemberg we assumed that a part of the reforestation takes place over natural regeneration and that only one young growth tending intervention is necessary instead of two for Norway spruce. Costs for administration were estimated to be equal for spruce and beech (Dieter, 2001, p. 160) and thus excluded from the calculation.

2.2.4. Sensitivity analysis: rotation length, interest rate and influence of risk

The effect of a change of the rotation length of spruce, a variation of the interest rate between 1% and 3% and the influence of risk was investigated. As we have to assume a higher risk towards biotic and abiotic damage of Norway spruce compared to European beech we investigated two different risk scenarios: Risk 1 is based on transition probabilities for spruce and beech used by Dieter (2001). A decrease of the rotation time by 10 years for spruce and an additional decrease of the LEV for spruce by 4% and for beech by 2% is the basis for the calculation of the LEV (Dieter, 2001, p. 161). Risk 2 instead uses the results of the study applied by Holec and Hanewinkel (2006) for the development of their insurance model and the findings of (Schmidt et al., 2009), who predict a 4–6 times higher vulnerability of Norway spruce compared to beech in a model based on data of the storm "Lothar". For Risk 2 an additional forced reduction of the rotation to 60 years and an additional reduction of the LEV of 15% for Norway spruce are the basis for the calculation, while LEV of beech is the same as in Risk 1.

3. Results

3.1. Biome shift

The final model we applied to model biome shift of Norway spruce had the following form:

$$\log \frac{\text{Prob}(y_i = 1)}{1 - \text{Prob}(y_i = 1)} = -2.722 \times 10^{-1} - 1.962 \times 10^{-2} \text{slp25} \\ - 6.962 \times 10^{-4} \text{asp25} - 7.849 \\ \times 10^{-1} \text{tmcm} + 5.251 \times 10^{-3} \text{psg} \\ - 7.713 \times 10^{-5} \text{prsa} \quad (2)$$

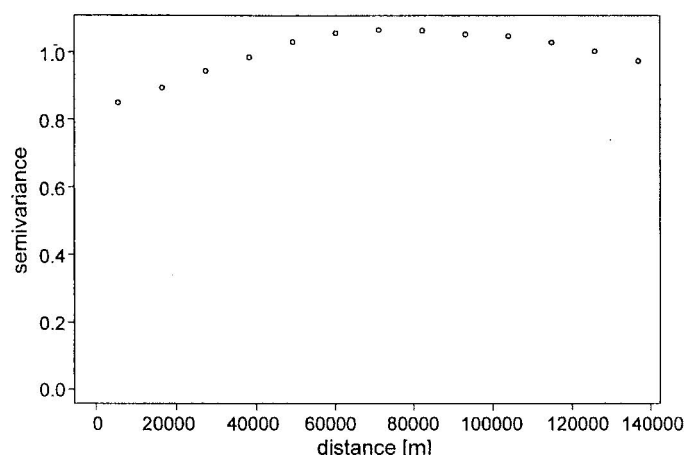


Fig. 1. Empirical semivariogram of the model residuals over distance.

The semivariogram of the model residuals (see Fig. 1) exhibits a visible but weak spatial autocorrelation which led us to accept (Eq. (2)) as a valid specification of (Eq. (1)).

Table 2 shows the results for the parameter estimations of the final model.

The explained deviance adjusted following Guisan and Zimmermann (2000) was 0.1802383, and the area under the receiver-operating-characteristic curve (AUC) was 0.7750909.

Table 3 gives the mean of predicted probabilities by (Eq. (2)) for relative frequency of plots with Norway spruce by altitude classes. The model underestimates the number of plots with Norway spruce in the lowest altitude class, but performs fairly well for altitude classes with more than 30 plots.

Optimising the threshold for transforming the predicted probabilities into presence/absence predictions by maximising Cohen's kappa gave us the relative confusion matrix shown in Table 4, where about 75% of observations were properly classified. This corresponds to a value of about 0.4154682 for Cohen's kappa.

Ten-fold cross-validating the model gave adjusted deviances with a mean of 0.1805363 a standard deviation of 0.002672381 and AUC with a mean of 0.775113 a standard deviation of 0.001919098. Accordingly, the mean of the relative confusion matrices of the cross-validations (Table 5) was similar to Table 2, their standard deviation being about 0.01 (see Table 6).

Table 2

Predictors with their parameter estimates, their standard errors and their z- and p-values.

	Estimate	S.E.	z value	Prob(> z)
Intercept	-2.722e-01	2.254e-01	-1.208	0.227116
slp25	-1.962e-02	2.652e-03	-7.398	1.39e-13
asp25	-6.962e-04	1.996e-04	-3.488	0.000486
tmcm	-7.849e-01	2.048e-02	-38.319	<2e-16
psg	5.251e-03	2.304e-04	22.787	<2e-16
prsa	-7.713e-05	9.851e-06	-7.831	4.86e-15

slp25: slope; asp25: aspect (both from a 25 m × 25 m digital elevation model); tmcm: temperature of the coldest month; psg: the sum over the growing season (May until October) of precipitation; prsa: annual sum of potential radiation.

Table 3

Number of plots (No.), arithmetic mean of predicted probabilities (Pred.) and observed species presence (Obs.) by altitude classes.

	- , 100 (m)	100, 350 (m)	350, 500 (m)	500, 750 (m)	750, 1000 (m)	1000, - (m)
No.	30	2276	3194	5067	2084	380
Pred.	0.15672173	0.3367920	0.5645457	0.7802523	0.8739853	0.9544131
Obs.	0.03333333	0.3084359	0.6042580	0.7738307	0.8613244	0.9552632

Fig. 2 shows the development of the area of Norway spruce under the different climate scenarios over time.

Especially for scenario A2, one can see that Norway spruce is being pushed back to the highest elevations in Baden-Wuerttemberg in the southwest (Black Forest area) and the east (Swabian Alb and pre-alps) of the state. For scenario A2 in the year 2100 Norway spruce will be restricted to forest areas distinctly above 1000 m asl in the Black Forest and pre-alpine area of Southwest Germany, according to our model.

Table 7 shows the results of the classification of the model when applied under different climate scenarios.

The model predicts the absence of the area of Norway spruce on 9–22% of the total forest area and a reduction of existing Norway spruce stands between 20% and 38%. There is not much difference between the scenarios B1 and A2 for the year 2030, which is in line with the predictions of the IPCC (IPCC 2007) that do not show distinct differences between the various scenarios for the next two decades. However, it is notable that Norway spruce will lose more than 20% of potential growth area within the next two decades from now on only for the reason of an increasing temperature. The extrapolation range of the model is reached to a large extent mainly for scenario A2 in 2100, where almost 50% of the forest area under investigation is predicted to reach climatic conditions that are not mirrored by present bioclimatic circumstances in southwest Germany. This area was excluded from the potential growth area of Norway spruce in our economic analyses. Expansion will not play a major role according to our model projections. Only in 2030 a potential increase of the area of Norway spruce in forests that are today dominated by other tree species would theoretical be possible to a visible extent. Summing up the potential area of expansion and presence, an area that we interpret as the potential growth area for Norway spruce, we can see a drastic decrease for both scenarios. The area suitable for Norway spruce reaches from 55% in 2030 (A2 and B1), over 40% (B1) and 32% (A2) in 2065 to 28% in 2100 for scenario B1. For scenario A2, only 5% of the total forest area in Southwest Germany is classified to be suitable for growing Norway spruce in 2100.

3.2. Economic results

3.2.1. Land expectation values

Table 8 shows the results of the calculations for the model stands of Norway spruce and European beech. For beech stands, the net values for stumpage are positive from 50 years on and reach more than 33,000 € at the age of 140. No costly pre-commercial thinnings are necessary. For beech one young growth tending intervention at age 10 was assumed to be necessary (550 €/ha) mainly to guarantee accessibility to the young forest. Costs for beech reforestation (1500 €/ha) are lower than Norway spruce due to an assumption of natural regeneration. For Norway spruce, stumpage values are positive at age 30 and reach more than 40,000 € at the age 140. Two young growth tendings, at age 10 and 20, and one pre-commercial thinning produced a deficit at age 35, but are assumed to be necessary for stability reasons. The resulting LEVs reach a maximum at age 130 (optimal rotation time according to LEV) with 1535 €/ha for beech and 5234 € for spruce at age 80. The LEVs do not take risk into account. The curve of the LEV for spruce is comparatively flat between ages 70–110 (less than 10% change) and is positive from the

Table 4

Confusion matrix divided by number of observations.

	Predicted	
	False	True
Observed		
False	0.1860180	0.1454225
True	0.1058246	0.5627350

Table 5

Mean relative confusion matrix for the cross-validation.

	Predicted	
	False	True
Observed		
False	0.1858645	0.1455759
True	0.1063618	0.5621978

Table 6

Standard deviations of relative confusion matrix for the cross-validation.

	Predicted	
	False	True
Observed		
False	0.011078249	0.007144571
True	0.012806374	0.014885730

age of 50 years on. For beech, LEV is positive after 90 years and rises considerably after 100 years. The differences in cash flows and the resulting LEVs between spruce and beech are mainly due to the difference in volume growth (13.4 m³/ha year of average total growth over 100 years for spruce compared to 8.15 for beech) and the difference in produced stem-wood.

Table 7

Classes of distribution of Norway spruce under different climate scenarios (share of total forest area) (see text). Exp. + pres. = potential distribution of Norway spruce (share of total forest area).

Scenario	Absence	Expansion	Presence	Exp. + pres.	Reduction	Extrapolation
B1 – 2030	0.22799	0.09209	0.46044	0.55253	0.20758	0.0119
B1 – 2065	0.21526	0.05886	0.3497	0.40856	0.30727	0.06891
B1 – 2100	0.19131	0.03545	0.25294	0.28839	0.36981	0.15049
A2 – 2030	0.22677	0.09378	0.46574	0.55952	0.20229	0.01142
A2 – 2065	0.19699	0.04382	0.28586	0.32968	0.34694	0.12639
A2 – 2100	0.09186	0.00177	0.04835	0.05012	0.38754	0.47048

Table 8

Cash flows and land expectation values (LEV) for model stands of beech and spruce.

Time (years)	European beech				Norway spruce			
	Costs (€/ha)	Stumpage (€/ha)	Thinnings (€/ha)	LEV (€/ha)	Costs (€/ha)	Stumpage (€/ha)	Thinnings (€/ha)	LEV (€/ha)
0	1500	0.0	0.0		2746	0.0	0.0	
10	550	0.0	0.0	–21196	550	0.0	0.0	–34414
20	0	0.0	0.0	–7775	776	–300.0	0.0	–15735
30	0	–360.0	0.0	–5679	0	1531.6	0.0	–7394
40	0	–71.0	0.0	–4068	0	5242.6	–154.6	–2553
50	0	472.8	50.0	–3024	0	11103.9	1090.9	1872
60	0	1446.7	101.8	–2195	0	15627.5	1808.6	3642
70	0	2927.0	254.3	–1471	0	20760.2	2361.8	4891
80	0	5205.0	434.3	–771	0	23838.2	3710.2	5234 ^a
90	0	8823.9	773.1	10	0	26752.0	2895.1	5107
100	0	14357.1	151.3	684	0	30178.6	2559.2	4928
110	0	18768.5	840.4	964	0	33026.9	4089.2	4821
120	0	24869.4	1377.5	1325	0	36268.1	1896.2	4461
130	0	30028.2	2871.0	1535	0	38765.7	5162.4	4345
140	0	33613.7	2174.4	1450	0	41082.4	3357.4	4066

^a Optimal rotation according to LEV, $r=0.02$.

3.2.2. Change in LEV under different climate scenarios

Table 9 shows how the different scenarios lead to changes in area suitable to grow Norway spruce and the resulting change in LEV. For the year 2000, the model predicts that around 70% of the total forest area of around 1.3 million ha is suitable to grow Norway spruce, which is equal to an area of approximately 927,000 ha. Under the two climate change scenarios this area will be reduced to between 740,000 ha (B1/A2-2030) and 66,000 ha (A2 - 2100). The resulting loss of area suitable for growing spruce will be between 190,000 ha (B1/A2- 2030) and 860,000 ha (A2 - 2100). Assuming the LEV of the optimal rotation time for Norway spruce (80 years) (5234 €/ha, see Table 6), the area suitable for growing spruce represents an overall LEV of 4.8 billion € in the year 2000. Following our predictions, this total LEV for the potential area of spruce will be reduced to between 3.8 billion € (B1/A2 - 2030) and 350 million € (A2 - 2100). If we assume that on the remaining area it will still be possible to grow beech (LEV of 1535 €/ha at an optimal rotation of 130 years), the overall reduction adds up to between 700 million € (B1/A2 - 2030) and 3.2 billion € (A2 - 2100) (between 600 and 2800 €/ha of total forest area). This represents the reduced amount forest investors would be willing to pay for forestland (LEV) in Southwest Germany associated with the climate change scenarios.

3.2.3. Sensitivity analysis

The influence of the interest rate on the results is considerable. For example, increasing the rotation of Norway spruce to be consistent with current "close-to-nature" silvicultural practices compared leads to a decrease of the difference in LEV of around 20% compared to of European beech (130 years) (Table 10). A decrease of the interest rate diminishes the relative difference between spruce and beech (less than 200% of difference compared to almost 300% with $i=2\%$) but significantly increases the absolute difference in LEV to values between 2 billion € (B1/A2 - 2030) and 10 billion € (A2 - 2100) for the total forest area. An interest

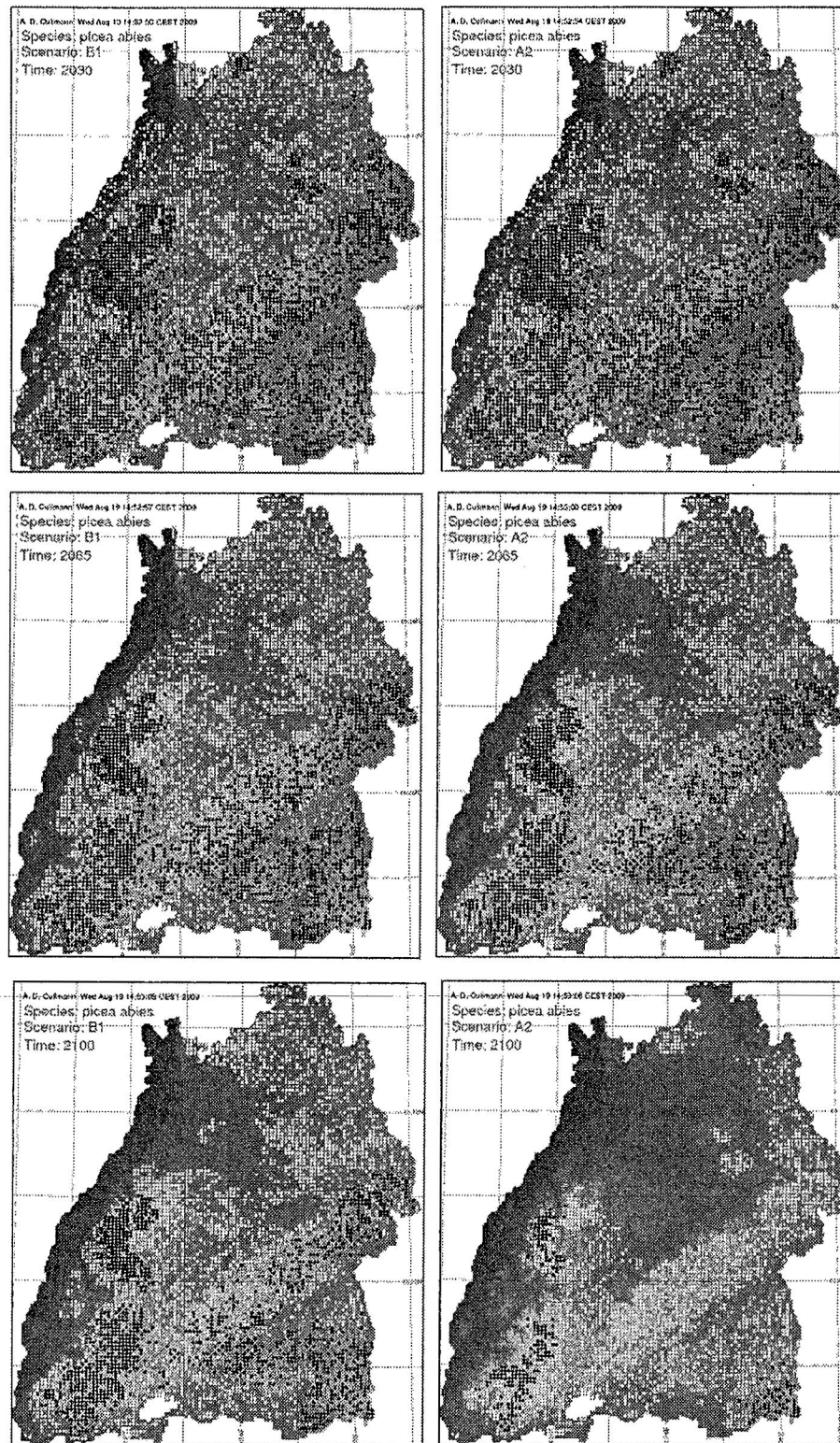


Fig. 2. Results of the biome shift model for Norway spruce in Southwest Germany – every pixel represents 1 plot of the National Forest Inventory. Black: area feasible for growing Norway spruce, white: area not feasible for growing Norway spruce, grey: no plot or extrapolation range of the model left column: Scenario B1 – years 2030 (upper), 2065 (middle), 2100 (lower row); right column: Scenario A2 – years as B1.

rate of 3% leads to the smallest absolute differences in LEV of all scenarios investigated, but delivers negative values for LEV of beech. Table 10 shows that the difference in LEV is reduced by around 25% for "Risk 1", while "Risk 2" reduces the difference in LEV compared to the first scenario to between 300 million and 1.3 billion Euro.

4. Discussion

4.1. Species distribution modelling

Guisan and Zimmermann (2000) give an overview of methods and background of predictive habitat modelling that is also the

Table 9
Changes in potential area of Norway spruce and in land expectation values (LEV in ha) assuming a shift from Norway spruce to European beech under different climate change scenarios. Total forest area = 1,323,119 ha.

Scenario – year	2000	B1 – 2030	B1 – 2065	B1 – 2100	A2 – 2030	A2 – 2065	A2 – 2100
Pot. spruce (share of total area)	0.7005602	0.55253	0.40856	0.28839	0.55952	0.32968	0.05012
Diff. – 2000	–	0.1480302	0.2920002	0.4121702	0.1410402	0.3708802	0.6504402
Ha spruce	926,925	731,063	540,573	381,574	740,312	436,206	66,315
Diff. – 2000 (ha)	–	195,862	386,351	545,350	186,613	490,719	860,610
LEV (spruce) (€)	4,851,522.892	3,826,383.434	2,829,361.692	1,997,159.826	3,874,790.615	2,283,101.534	347,091.267
Diff. – 2000 (LEV) (€)	–	724,491.948	1,429,112.396	2,017,250.474	690,281.370	1,815,168.247	3,183,395.602

methodological basis for modelling biome shifts for tree species in this study. Kolling (2007) has published basic climate envelopes for 27 tree species in Germany and has initiated a discussion on the validity and usefulness of this methodology as a tool for forest management (Bolte et al., 2008). Although simple bioclimatic envelope models may have a number of advantages (e.g. they are rather easy to understand for practitioners), they can be applied only when users of the models have thorough understanding of their limitations and uncertainties (Heikkinen et al., 2006). A major challenge in the development of new bioclimatic envelopes under climate change will be the integration of uncertainty.

Biome shifts for tree species are usually modelled based on a presence/absence approach using national forest inventory data and climate parameters such as (mean) temperature, (mean) precipitation, radiation, and soil-related parameters (Zimmermann et al., 2006; Thuiller et al., 2008). Climate parameters are often taken from downscaled regional climate models (RCM), based on the results of global circulation models (GCM) and predicted into the future for different climate scenarios (Bohner, 2005). A similar approach for modelling biome shifts for the main tree species in Switzerland is discussed by Zimmermann and Bugmann (2008).

Statistical approaches such as generalised linear models (GLMs), as used in this study, can include more variables and deliver an unambiguous solution, while simple geometric climate envelopes (Kolling, 2007) are difficult to design with multiple explaining variables. Furthermore, statistical models offer the opportunity of using statistical quantitative criteria such as AIC, BIC, or deviance to evaluate parameter selection and model fit.

Mbogga and Hamann (2008) analysed sources of uncertainties in bioclimatic envelope models and found that the choice of the global circulation model can be responsible for a large part of observed variation. In this study, we selected two conservative IPCC scenarios (A2 and B1), which might be an optimistic assumption: according Anderson and Bows (2008) anything less than 650 ppm CO₂ is increasingly unlikely. Using scenarios like A1FI would have shown a more drastic change than depicted in our study.

We simplified the warming linked to the increase of the CO₂ concentration of the two scenarios by assuming a similar increase of the temperature at each plot of the NFL. This assumption is warranted by our objective, which is to show that the ecological effects of climate change have economic consequences (Parry et al., 2007, 68 ff) and not to deliver a spatially explicit analysis and interpretation of temperature and species shift. We also did not assume any change in precipitation. An application of three different regionalisation approaches (STAR, REMO, WETTREG) for southwest Germany showed ambiguous results for the development of precipitation under a B2 - scenario for the years 2020–2050 (AG-KLIWA, 2006, p. 48), which is a sign that projecting climate parameters such as precipitation is still linked to large uncertainties.

The potential impacts of projected climate change on tree species distribution are usually assessed using single-species bioclimatic envelope models (Heikkinen et al., 2006; Kolling, 2007). There is an increasing interest in this technology with global change and new methods to model distribution (Elith et al., 2006) are applied and future challenges to predict the impact of the expected change to plant distribution are being addressed (Thuiller et al., 2008). A key challenge for future research in general plant distribution modelling is the integration of factors like land cover, direct CO₂ effects, biotic interactions and dispersal mechanisms (Heikkinen et al., 2006) as well as the adaptation potential of long living organisms like trees. The shortcomings and uncertainties of these approaches have to be carefully evaluated (Heikkinen et al., 2006):

Table 10

Sensitivity analysis – difference in LEV (€) to the basic scenario (basic diff. 2000) under different assumptions for rotation time, interest rate and risk influence.

Scenario – year	B1 – 2030	B1 – 2065	B1 – 2100	A2 – 2030	A2 – 2065	A2 – 2100	LEV spruce	LEV beech
Basic diff. 2000 ^a	724,491,948	1,429,112,396	2,017,250,474	690,281,370	1,815,168,247	3,183,395,602	5,234	1,535
Diff. <i>t</i> spr. = 130 ^a	550,371,012	1,085,646,345	1,532,434,126	524,382,441	1,378,919,377	2,418,313,501	4,345	1,535
Diff. <i>i</i> = 1%	2,259,459,074	4,456,945,282	6,291,160,171	2,152,767,203	5,660,930,223	9,927,994,503	24,661	13,125
Diff. <i>i</i> = 3%	235,229,746	464,007,566	654,965,618	224,122,175	589,353,086	1,033,592,354	300	–901
Diff. risk 1 ^a	624,798,409	1,232,459,730	1,739,667,211	595,295,369	1,565,392,460	2,745,345,220	4,695	1,505
Diff. risk 2 ^a	311,615,758	614,684,461	867,652,205	296,901,233	780,733,355	1,369,230,171	3,096	1,505

Diff. *t* spr. = 130 = rotation for spruce = 130 years.^a Interest rate = 2%. Risk 1, 2 see text.

A common problem in presence-absence models all over Europe is the human influence and the lack of the inclusion of potential adaptation processes (Bolte et al., 2008). In Southwest Germany almost the whole forest area has been subject to human interventions. Studies dealing with potential adaptation of tree species to climate change are in a very early stage (Bolte et al., 2007).

In our study we concentrate on the biome shift from Norway spruce to European beech. Spruce is an example of a group of highly productive coniferous trees that include species like silver fir (*Abies alba*) that will suffer more from an expected warming due to climate change than deciduous trees. The process of biome shift of Norway spruce in Southwest Germany is already ongoing. From 1987 to 2002 its area decreased by more than 75,000 ha from more than 42% of the total forest area to 36% (around 483,000 ha) (BMELV, 2005). Beech represents in our study a large group of hardwoods like oak (*Quercus spec.*), maple (*Acer spec.*) or ash (*Fraxinus spec.*), etc., that show similar economic productivity. We did not take into account that under climate change a part of the area of Norway spruce may be overtaken by more drought resistant conifers of similar or even higher productivity such as Douglas-fir (*Pseudotsuga menziesii*), but on the other hand we assume that even under severely deteriorating conditions such as in scenario A2 in the year 2100, timber production with beech or species with similar economic productivity will still be possible.

In our model we concentrate on the change of species distributions due to changes in the bioclimatic conditions. We do not take into account other parameters that determine species i.e. site conditions or goals of forest owners such as nature protection, ecology or recreation or the historical development of species distribution that lead to a multitude of tree species. The prediction of the model for the year 2000 of the potential area suitable for growing Norway spruce (around 70% of the total forest area) is therefore distinctly higher than the area actually occupied by Norway spruce (around 40%).

4.2. Economic evaluation

SILVA is an empirical growth model that is insensitive to climate change and a more appropriate approach for our financial evaluation would have been to use a process-based model. However, such models are not yet viable at the spatial scales associated with the forest management problems at the centre of our study. Basing volume estimates and, thus, cash flow on the mean values over the entire area is a simplification consistent with existing limitations on spatial simulations of the ecological and financial effects of climate change.

We designed the model stand of European beech as a low input model with rather low costs for regeneration and young growth tending, while we assumed higher costs for Norway spruce not only for planting but also for young growth tending and pre-commercial thinning in order to enhance the stability of the Norway spruce stands. The Faustmann-model is sensitive to these costs, which appear early in the cash-flow cycle. Assuming similar

costs for beech than for spruce would distinctly increase the difference between spruce and beech. The relative difference between spruce and beech in land expectation value that we found with our model stands is similar to that of Dieter (2001) and to that reported by Knoke et al. (2008) and (Mohring, 2004), but the absolute difference is of course different due to a different price level (Dieter, 2001 assumes prices of the year 1995). The optimal rotation times for spruce and beech of our study are also similar to those found and applied by Dieter (2001) and Beinhofer (2008, only spruce), we therefore think that management schemes, cash flows and the adopted interest rates of the species models we use are in line with the standard approaches that are used in Germany at the moment.

We used the classical Faustmann approach to represent the change in the value of forestland induced by climate change. We did not use approaches that level out the effect of different production times in the economic analysis such as annuities that are currently discussed in German forestry economics (Mohring et al., 2006). We instead analysed the influence of a variation of the rotation time. We think that this is useful as one major adaptation strategy to climate change will be an adaptation of the production times of different tree species.

The Faustmann approach implies some basic assumptions such as perfect market, constant timber prices and costs and constant and known future timber yields (Klemperer, 1996, p. 220; Navarro, 2003; Tahvonen and Viitala, 2007). Timber and input prices, however, are subject to periodic fluctuations and the forecasted timber yield is subject to various risks. It has therefore been criticised as to be unrealistic and many scientific endeavours were undertaken to include e.g. risk and uncertainty in the formula (i.e. Reed, 1984; Dieter, 2001; Zhang, 2001). Including the risk of volatile timber prices in our model as this can be found in several studies (e.g. Knoke and Wurm, 2006) would not have significantly changed the results of our study as both species will be subject to fluctuations in timber prices. However, there are clear signs that there are differences in the impact of abiotic and biotic risks on the different tree species especially between spruce and beech in our study area (Schmidt et al., 2009). Tree species is one of the widely acknowledged predisposing factors for storm damage (Lohmander and Helles, 1987; Peterson, 2000; Mayer et al., 2005; Schutz et al., 2006; Hanewinkel et al., 2008). Knoke et al. (2008), based on data of Mohring (2004), report about a higher standard deviation of the net present value of net revenues of Norway spruce forests compared to European beech forests as an expression of the higher economic risk of managing spruce.

Rather than explicitly modelling risk in our economic analysis (e.g. Dieter, 2001; Knoke and Wurm, 2006), we focused on how risk affects the LEV within a sensitivity analysis based on existing empirical studies for several reasons: published studies that might be relevant are based on risk-data (Konig, 1995) that are either regionally limited (few thousand hectares) or based on a period in time (1990 and 1999) that refers to the past. Despite data on risk for spruce or spruce-dominated forests in the area (Holec and Hanewinkel, 2006; Hanewinkel et al., 2008), the database for beech

is still scarce. It is not adequate for an application to a large scale and into the future in the present study and it would not justify a detailed modelling of risk as the prediction of the development of future risks under changing climatic conditions is subject to large uncertainties. Although a general trend towards higher wind speeds is not detectable for the whole of Europe (Albrecht et al., 2009), for some areas, e.g. southernmost Sweden, an increasing probability of exceeding critical wind speeds was indicated by most of the climate change scenarios calculated by Blennow and Olofsson (2008). This has to be taken into account in further risk modelling approaches.

The introduction of risk in the calculation not only reduces the LEV of the two species in a different way but also leads to a different probability distribution of the underlying cash flows, i.e. the standard deviation of these cash flows will be higher for spruce than for beech. This leads to the fact that managing Norway spruce under climate change, as simulated in our study will be subject to a higher uncertainty than European beech. Risk averse forest owners will therefore tend to achieve higher shares of European beech to reduce this standard deviation and thus the uncertainty (Knoke and Wurm, 2006).

The cash flows and the resulting LEVs (Table 2) that do not encompass any further management or administration cost, indicate that - under the given price-cost relationships - managing for beech will be difficult from an economic point of view. This is in line with the results reported by Mohring (2004) and other authors (e.g. Dieter, 2001). Applying higher interest rates than 2% or integrating standard administration costs leads to negative values for the LEV. As a consequence, private or public forest owners would be unlikely to make a living off their forestland if productive coniferous species are systematically excluded and replaced by hardwood species on large areas. Safeguarding forest functions such as recreation that need financial input from the forest owner and that have so far been financed by timber production and the labour that is linked to forest production will therefore be more and more difficult.

Conclusions - outlook

It is insufficient to restrict discussion about climate change effects to ecological aspects. Instead, methods to calculate associated financial effects are also needed to advance the process of managing forests to ameliorate the risks associated with a changing climate. A first step is to downscale the projections for [PCC scenarios of GCM and RCM to a level relevant for forest management decisions as a basis for comprehensive models that are able to predict future distributions of our tree species. As a next step, biome shifts for major tree species have to be assessed. Therefore the progress that has been made in modelling plant species distribution under changing climatic conditions (Elith et al., 2006) has to be used and extended to the most important tree species in Europe. As a first approach, simple bioclimatic envelopes maybe useful (Kolling, 2007), but the implementation of very simplistic suitability tables for tree species under changing climatic conditions (Roloff and Grundmann, 2008) seems to be not adequate in this respect. Tebaldi et al. (2006) show that individual model projections for the 21st century across three different scenarios are in agreement in showing greater temperature extremes consistent with a warmer climate. In addition to that, climate change affects forests by altering the frequency, intensity, duration, and timing of the major damaging agents such as fire, insects or windstorms (Dale et al., 2001). This will have distinct consequences on the distribution of major tree species not only in Europe.

In order to improve the database for any kind of risks that are linked to changing environmental conditions and that should be

used for the economic evaluation we need an idea about the approach to be used. As a general modelling approach, forest damage of different kinds can be modelled in a three-stage procedure: (1) Initially, the probability of damage has to be assessed. (2) Subsequently, the amount of damage, given that a damage event occurred, must be described. (3) Eventually, autoregressive techniques can be applied to correct the dependence of damage in time and space. This approach is a variant of the expected value approach that is very common in risk modelling (Haimes, 2004) and is often used for risk assessment in forest planning models (Gadow, 2000). There is a wide array of statistical modelling techniques available for the different steps. Ideally the models are built on a long-term and large scale database such as national forest inventory data or level I/level II - monitoring data on a European scale.

When taking into account economic aspects, we need destruction probabilities for the major tree species expressing abiotic and biotic risks. The risk of volatile timber prices should as well be taken into account. Monte Carlo simulation techniques seem to be a useful tool to integrate different risks in economic calculations (Dieter, 2001; Knoke and Wurm, 2006; Kurz et al., 2008). Due to the largely subjective character of risk (Kaplan and Garrick, 1980; Haimes, 2004), it is crucial to take into account attitude towards risk, usually in the form of risk aversion (Plattner, 2006). Adaptation strategies such as active forest transformation from conifers to hardwoods have to be designed such that the economic losses that are linked to these activities are minimised. This requires clear priorities where the most vulnerable forest stands are and where to start with the transformation.

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