

Modelling bark beetle disturbances in a large scale forest scenario model to assess climate change impacts and evaluate adaptive management strategies

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Abstract To study potential consequences of climate-induced changes in the biotic disturbance regime at regional to national scale we integrated a model of *Ips typographus* (L. Scol. Col.) damages into the large-scale forest scenario model EFISCEN. A two-stage multivariate statistical meta-model was used to upscale stand level damages by bark beetles as simulated in the hybrid forest patch model PICUS v1.41. Comparing EFISCEN simulations including the new bark beetle disturbance module against a 15-year damage time series for Austria showed good agreement at province level (R^2 between 0.496 and 0.802). A scenario analysis of climate change impacts on bark beetle-induced damages in Austria's Norway spruce [*Picea abies* (L.) Karst.] forests resulted in a strong increase in damages (from $1.33 \text{ Mm}^3 \text{ a}^{-1}$, period 1990–2004, to $4.46 \text{ Mm}^3 \text{ a}^{-1}$, period 2095–2099). Studying two adaptive management strategies (species change) revealed a considerable time-lag between the start of adaptation measures and a decrease in simulated damages by bark beetles.

Keywords Natural disturbances · Climatic change · *Ips typographus* · Scaling · Adaptation

Introduction

Key drivers of forest ecosystem dynamics are natural disturbances, playing an important role in natural forest development. Consequently, disturbances are highly relevant factors in the sustainable management of forest ecosystems. Climate change has the potential to distinctly alter disturbance regimes which could negatively affect the sustainable provision of important forest services and functions (e.g., Ayres and Lombardero 2000; Dale et al. 2000). According to Schelhaas et al. (2003) windthrow was the most important abiotic natural disturbance in European forests over the last century whereas bark beetles were the most important biotic disturbance agent. Since poikilothermal organisms are directly dependent on the climate regime several authors expect increasing damages from insects as for instance bark beetles under warmer climatic conditions (e.g., Harrington et al. 2001; Bale et al. 2002). The increasing risk from biotic disturbances results from positive feedbacks of changes in climate on essential elements of the herbivore–host system.

The temperature regime directly affects life cycles and winter survival of insects which are generally limited by the thermal environment (e.g., Wermelinger and Seifert 1999; Netherer and Pennerstorfer 2001; Wermelinger 2004). Thus, an increase in temperature is expected to increase the reproductive capacity and number of completed life cycles per year of important biotic disturbance agents such as bark beetles (Bale et al. 2002). Moreover, climate change is likely to cause shifts in outbreak ranges of insect species (e.g., Parmesan et al. 1999; Williams and

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Liebhold 2002). Due to the wide latitudinal and altitudinal distribution of the main European tree species the spatial distribution of important insect herbivores is in many cases limited by harsh environmental conditions rather than host availability. For instance, for the Norway spruce [*Picea abies* (L.) Karst.] bark beetle *Ips typographus* (Scol. Col.) the spatial distribution of the host species by far exceeds the thermally feasible area of insect development. A shift in climatic conditions could trigger a dramatic expansion of herbivores to host areas currently not susceptible to these disturbance agents. Additionally, an increase in environmental stress factors for the host species may reduce host resilience to infestation by insects (e.g., Rouault et al. 2006). Drought stress, for instance, has been identified as a major factor increasing predisposition of Norway spruce to attacks of *I. typographus* (e.g., Wermelinger 2004; Rouault et al. 2006) and is likely to increase under warmer climate conditions.

Addressing these manifold interactions, considerable efforts have been made to investigate prominent biotic disturbance agents in North America (e.g., Williams and Liebhold 2002; Sturtevant et al. 2004; Candau and Fleming 2005). For the most important European bark beetle, *I. typographus*, a recent focus on bark beetle ecology (cf. Okland and Bjornstad 2003, Wermelinger 2004, Eriksson et al. 2007, 2008) resulted in increased understanding of the herbivore–host complex at individual tree to stand level. This inter alia facilitated the design of models to assess climate change impacts on *I. typographus* disturbances at stand and forest management unit level (e.g., Seidl et al. 2008). Alongside detailed small scale models accounting for the full complexity of bark beetle ecology, however, assessment tools at larger scales (e.g., province-, country-, continental-level) are required to support policy decisions under changing environmental conditions.

A frequent approach to address larger spatial scales with regard to risks from biotic disturbances is predisposition assessment based on climatic gradients (e.g., Baier et al. 2007; Jönsson et al. 2007). Such approaches, however, widely neglect the dynamic interactions of disturbances, management and the ecosystem. Disturbances dynamically influence their environment (e.g., modifying host availability). Consequently feedbacks between disturbances and forest dynamics need to be accounted for in comprehensive large scale risk assessments. Vice versa, disturbances have profound impacts on forest resources and are thus essential elements in realistic models of large scale forest development (cf. Schelhaas et al. 2002; Kurz et al. 2008). Thus, despite the considerable trade-offs necessary to foster applicability at larger scales (e.g., with regard to processes such as detailed population dynamics) an integration of biotic disturbances in large-scale forest models is of high priority. The model EFISCEN was widely applied over the

last years with regard to questions of forest resource development at national to continental scales (e.g., Nabuurs et al. 2003; Schröter et al. 2004; Pussinen et al. 2005; EEA 2006; Schelhaas et al. 2006; Nabuurs et al. 2007). Although EFISCEN contains a module of natural disturbances (Schelhaas et al. 2002) the representation of biotic disturbances, as for instance bark beetles, is currently not satisfactorily, particularly with respect to studying impacts of climate change.

Therefore, our objectives were (1) to develop and integrate a climate-sensitive approach of simulating bark beetle damages in the large-scale forest model EFISCEN; (2) to evaluate the approach against a 15-year time series of independent data on bark beetle damage at regional level; (3) to study potential climate change impacts on the disturbance regime, and (4) investigate the effects of possible adaptive management strategies on bark beetle damages.

The development of a bark beetle disturbance module for the EFISCEN framework built on the hybrid stand level model PICUS v1.41 (Lexer and Hönninger 2001; Seidl et al. 2005) which includes a detailed sub-model of bark beetle induced mortality of Norway spruce (Seidl et al. 2007a). A two-stage meta-modelling approach was used to extract process behaviour from PICUS and integrate it into EFISCEN. Austria's Norway spruce forests [1.99 million ha (Mha)] were chosen as study object since they represent wide ecological gradients over strongly heterogeneous landscape from the colline to the subalpine vegetation belt in the Eastern Alps. The extended EFISCEN model was evaluated by comparing independent province level bark beetle damage data from Austria with EFISCEN simulation results. Finally, the extended model was applied to estimate the impacts of climate change on future damages from bark beetle disturbances, and to study the mitigation effect of alternative forest management strategies.

Materials and methods

Basic model concepts

EFISCEN v3.2

EFISCEN is an area-based matrix model that is especially suitable for scenario analysis at the regional or country level. The core of the EFISCEN model was developed in the late 1980s at the Swedish Agricultural University (Sallnäs 1990). EFISCEN v3.2 is an extension of the latest model version (Schelhaas et al. 2007) allowing the inclusion of natural disturbances (cf. Schelhaas et al. 2002). National forest inventory data are used as input for the EFISCEN model, including forest area, volume and net annual increment by age classes. Per country, forest

types can be distinguished by region, owner class, site class and tree species, depending on the available input data. The state of the forest is depicted as an area distribution over age and volume classes in a matrix. For each forest type a separate matrix is set up. Forest development is simulated by moving forest area between cells in the matrix (Fig. 1). Ageing is simulated by moving area to a higher age class, while volume growth is simulated by moving area to a higher volume class. Thinning and natural mortality are simulated by moving area one volume class down. In case of a final felling, area is moved to a bare forest land class outside the matrix. Regeneration is simulated by moving area into the first age–volume class of the matrix again.

Management is controlled at two levels in the model. First, a basic thinning and final felling regime is incorporated. This regime defines per forest type the probability that a thinning or final felling is carried out depending on stand age. Second, total required harvest volume from thinnings and final felling is specified for the country, region and/or species per time step. Taking into account the actual state of the forest and the constraints set by the basic management regime, the model tries to fulfil the specified felling levels. Other variables that can be included in scenario analysis are changes in forest area, changes in species composition by regenerating with a different species, and growth changes due to changing environmental conditions. The default timestep of the simulations is 5 years. EFISCEN has been applied in a number of continental scale studies recently, assessing the future development of European forest resources (e.g., Nabuurs et al. 2003; Schelhaas et al. 2006; Nabuurs et al. 2007). Moreover, the model has been adopted for the application under climate change by means of accounting for changed growing conditions in implementing growth responses from process models (e.g., Schröter et al. 2004; Pussinen et al. 2005). Climate drivers are not explicitly considered as input in EFISCEN but model parameters are updated according to

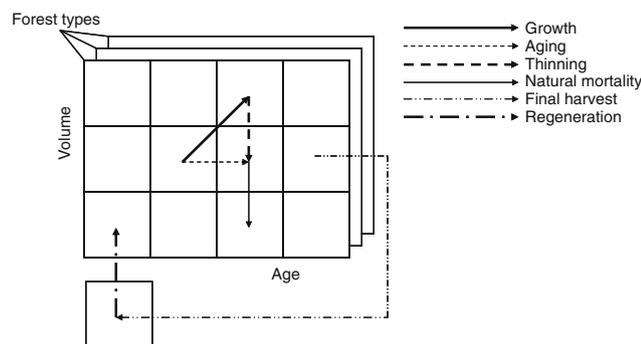


Fig. 1 Structure and simplified processes of the matrix model EFISCEN v3.2

meta-information on climate change effects. A more detailed model description can be found in Pussinen et al. (2001) and Schelhaas et al. (2007).

Schelhaas et al. (2002) extended EFISCEN with a module to simulate the impact of natural disturbances on forest resources. Three types of disturbances are considered: storm, fire and insect damage. Disturbance impacts in the model framework can either affect a part of the stand (non-stand replacing disturbance) or the total stand (stand-replacing disturbance). Non-stand replacing disturbances are simulated by moving area one volume class down, while stand-replacing disturbances are simulated by moving area to the bare forest land class. Each cell in all matrices is assigned a relative susceptibility, according to variables such as species, age, and thinning status. For storm and fire, each year a severity index is drawn randomly from observed severity distributions. The combination of severity, susceptibility and the actual distribution of area over the matrix then yields the total damage level. Insect damage is considered to stay at a constant “background” level, but can be increased by large storm events and high fire severity mediating warm and dry years. In an indicative study for Switzerland the EFISCEN disturbance module was parameterised with statistical disturbance data on the study region to investigate the influence of natural disturbances on forest resource development (see Schelhaas et al. 2002). Whereas the integration of the disturbance module was found to improve EFISCEN predictions of forest development (e.g., standing stock) compared to an “un-disturbed” model variant (cf. Schelhaas et al. 2002); the investigative power of the approach with regard to climate change was strongly limited by the required empirical parameterisation (distribution of annually damaged area) and the lack of direct climate dependency of, for instance, insect damages.

PICUS

PICUS v1.41 is a modular forest modelling framework centred around a hybrid patch model which incorporates a number of flexible sub-models for scenario analysis (e.g., forest management, bark beetle damage, rockfall protection; Seidl et al. 2005; Seidl et al. 2007a; Woltjer et al. 2008). Here, besides a brief overview of the general model logic the bark beetle disturbance sub-model will be described in more detail.

The hybrid model approach adopted in PICUS aims at combining the strengths of patch models and process based production models while circumventing limitations of the individual approaches (see Mäkelä et al. 2000). Spatial core structure of PICUS is an array of 10 m × 10 m patches with crown cells of 5 m in depth. In extension to classical patch models (compare Shugart 1984; Botkin

1993) spatial interactions between the patches are taken into account with regard to a detailed three-dimensional light regime and spatially explicit seed dispersal. Inter- and intra-species competition, seed dispersal and mortality are modelled based on the approach presented by Lexer and Hönninger (2001) whereas stand level net primary production is modelled according to the simplified physiological principles of radiation use efficiency of the 3-PG model (Landsberg and Waring 1997). The hybridisation of both concepts is described in Seidl et al. (2005). The model has been successfully evaluated with regard to the simulation of equilibrium species composition over broad environmental gradients in the Eastern Alps as well as against long-term growth and yield data of uneven-aged, multi-species stands (Seidl et al. 2005). The latest version of PICUS v1.41 includes a process-based soil model of dynamic C and N cycling (Currie et al. 1999) addressing interactions between aboveground production processes and belowground C and N dynamics (cf. Seidl et al. 2007b).

PICUS v1.41 contains a bark beetle disturbance sub-model which includes (1) the stochastic computation of the annual infestation risk for a simulated forest stand; (2) the estimation of damage intensity if an infestation occurs; and (3) the spatial distribution of bark beetle induced Norway spruce mortality within the simulated stand (Seidl et al. 2007a). Annual potential beetle generations are calculated according to length of photoperiod and thermal requirements for beetle development. The approach of calculating potential annual bark beetle generations adopted within the PICUS bark beetle disturbance sub-model is described in detail in Baier et al. (2007). In the current version, the simulation of potential generations does not account for a perennial bark beetle gradation—i.e., the number of potential annual insect generations are used as a proxy for beetle development and are transformed into a stand level hazard score (Netherer and Nopp-Mayr 2005). A stand predisposition index is adopted from Lexer (1995) and Netherer and Nopp-Mayr (2005), including four stand level predisposition indicators (share of host trees in a stand, stand density, stand age, and Norway spruce drought index, SMI). Stand predisposition and the potential insect generation score are combined to derive an annual probability of bark beetle damage (pBB) at stand level using the bark beetle infestation data set of Lexer (1995) for calibration (cf. Seidl et al. 2007a). Damage intensity (iBB), i.e., the amount of damaged Norway spruce trees per infestation, is calculated according to the empirical findings of Lexer (1995) using a stand hazard index combining south- and east-exposed stand edges, drought stress, and the proportion of Norway spruce host trees in the stand as predictors (see Lexer 1995) (Eqs. 1–3).

$$iBB = \frac{1}{1 + e^{3.9725 - 2.9673 \cdot SHI}} \quad (1)$$

$$SHI = SEE \cdot SMI \cdot HTS \quad (2)$$

$$SMI = 1 - \frac{\sum_{bgs}^{egs} AET}{\sum_{bgs}^{egs} PET} \quad (3)$$

iBB	annually damaged relative stem number (0–1)
SHI	stand hazard index
SEE	stand edge index (cf. Lexer 1995) (dimensionless); currently set to 1
SMI	soil moisture index over the growing season (0–1)
HTS	host tree share (0–1)
AET	actual evapotranspiration (mm)
PET	potential evapotranspiration (mm)
bgs	begin of growing season (date)
egs	end of growing season (date).

A more detailed description of the bark beetle disturbance sub-model alongside a thorough sensitivity analysis can be found in Seidl et al. (2007a). Recently, the sub-model was successfully employed to assess the impacts of bark beetle disturbances on timber production and carbon sequestration under climate change at the forest management unit level (Seidl et al. 2008).

Model development

A statistical meta-model of bark beetle damage

We chose a meta-model approach (i.e., a simpler statistical model of processes in the detailed PICUS model, cf. Urban et al. 1999) to introduce bark beetle disturbances into the large scale model EFISCEN. The two-stage modelling approach (i.e., separate estimation of pBB and iBB) was retained in the meta-model design. In order to derive multivariate regression models for pBB and iBB PICUS simulations were conducted over an array of environmental and stand conditions for generic stands of 1 ha. Simulations covered all combinations of a mean annual temperature gradient from 2 to 15°C (1°C interval) and a mean annual precipitation gradient from 500 to 2,000 mm (100-mm intervals). All other site parameters (e.g., soil conditions, diurnal and intra-annual variation of climate parameters) were kept constant. For every combination of temperature and precipitation a variety of stand conditions were assessed within PICUS. Stand structure (i.e., stem number, diameter, height of trees) was taken from yield tables (Marschall 1975) for an average site index for Austria (cf. Schadauer 1999). The studied array of stand age ranged from 40 years (assumed minimum age for *I. typographus* damage) to 120 years (10-year interval), stand density was studied from

60 to 100% of yield table stocking density (20% intervals). Moreover, the influence of mixed species on simulated bark beetle damage in PICUS was accounted for by simulating three levels of non-host species share in a stand (corresponding to 100, 50 and 10% Norway spruce share, respectively). Target variables of the PICUS simulations were the annual probability of bark beetle damage (pBB) and the soil moisture index (SMI), the latter being a main predictor of annual damage intensity (iBB , see Eq. 1). In total, the combination of climate and stand conditions resulted in 18,144 PICUS estimates of pBB and SMI as basis for the development of the statistical meta-models.

A logit model (function call `glm()`, error distribution: binomial, link: logit, R Development Core Team 2006) containing mean annual temperature and precipitation, stand age, relative stocking density and host tree share as explanatory variables was fitted to the PICUS results (Eq. 4). Host tree share was included as categorical predictor with three levels using dummy coding. Only model parameters which had been found influential on pBB in a multiple sensitivity analysis of the PICUS model (Seidl et al. 2007a) were included in the meta-model. First order interactions between climatic predictors and stand structure predictors were allowed in line with the PICUS model logic on combining site- and stand-level predisposition factors. Logarithmic transformation of both climate variables was necessary in order to achieve a satisfactory residual distribution. The model was found to be unbiased and achieved a R^2 value of 0.923. Model parameters as well as a closer analysis of model behaviour and fit can be found in the Appendix 1.

$$pBB = \frac{e^{z_{ijklm}}}{1 + e^{z_{ijklm}}}$$

$$z_{ijklm} = \mu + a_i + b_j + c_k + d_l + e_m + (a \cdot b)_{ij} + (a \cdot c)_{ik} + (a \cdot d)_{il} + (a \cdot e)_{im} + (b \cdot c)_{jk} + (b \cdot d)_{jl} + (b \cdot e)_{jm} + \varepsilon_{ijklm} \quad (4)$$

pBB	probability of bark beetle damage
z_{ijklm}	linear combination of predictor variables
μ	intercept
a_i	logarithmic mean annual temperature ($i = 2-15^\circ\text{C}$)
b_j	logarithmic mean annual precipitation ($j = 500-2,000$ mm)
c_k	stand age ($k = 40-120$ years)
d_l	stocking density relative to fully stocked yield table stands ($l = 0.6-1.0$)
e_m	host tree share (categorical, $m = 10; 50; 100\%$)
ε_{ijklm}	error term.

Damage intensity is simulated in PICUS applying a logistic regression model using host tree share and SMI as

main predictors (Eq. 1). The same calculation was applied within the EFISCEN environment, approximating SMI by means of a generalised linear model (GLM, function call `glm()`, error distribution: gaussian, link: identity, R Development Core Team 2006) with mean annual temperature and precipitation as predictors (Eq. 5).

$$SMI_{ij} = \mu + a_i + b_j + (a \cdot b)_{ij} + \varepsilon_{ij} \quad (5)$$

μ	intercept
a_i	mean annual temperature ($i = 2-15^\circ\text{C}$)
b_j	(precipitation) $^{-2}$; ($j = 500-2,000$ mm)
ε_{ij}	error term.

Besides temperature and precipitation also soil water holding properties play a role in determining soil moisture conditions (i.e., SMI) in PICUS. However, since soil conditions within the simulation units in EFISCEN are highly variable and detailed information on forest soils at large scales are limited values for SMI were derived utilising an average soil water holding capacity of 156 mm (cf. Lexer and Hönninger 1998). The GLM achieved a good and unbiased approximation of the PICUS simulation with $R^2 = 0.945$. Parameter values and detailed analysis of the SMI meta-model can be found in Appendix 2. It was subsequently applied to derive the SMI required in Eq. 1 to estimate the share of damaged Norway spruce volume in the EFISCEN framework.

Integration into EFISCEN v3.2

The statistical meta-model of bark beetle damages was integrated into EFISCEN v3.2, henceforward in short referred to as EFISCEN. The integration in general followed Schelhaas et al. (2002), treating stand-replacing disturbances as area transitions to bare forest land and non-stand replacing disturbances as area transitions to a lower volume class (cf. thinnings). However, in the present approach climatic drivers were explicitly considered in the simulation of biotic disturbances. To transfer annual stand level estimates of bark beetle damages by the two-stage meta-model to the area matrix concept of EFISCEN (5-year time steps) we developed a scaling approach that (1) preserved the interannual climate variability in calculating annual estimates of pBB and iBB ; and (2) accounted for the occurrence of multiple damages per area unit in a matrix cell for the 5-year prediction periods. Let I denote the set of years in the 5-year period (i.e., $I = \{1, 2, \dots, 5\}$) and Y_n represent the n th subset in $Y \subseteq I$. Treating damage probability as analogue to area share per matrix cell, the area subject to damage in all the years y of subset Y_n was calculated according to Eq. 6. Corresponding damage

intensities were derived by a sum over the annual meta-model estimates for years y in Y_n (Eq. 7).

$$sBB_{Y_n} = \begin{cases} qBB = 1 - pBB \\ \prod_{y \in Y_n} pBB_y \cdot \prod_{z \in I \setminus Y_n} qBB_z \end{cases} \quad (6)$$

$$iBB_{Y_n} = \sum_{y \in Y_n} iBB_y \quad (7)$$

The share of forest area in a matrix cell subject to (1) five subsequent bark beetle attacks (i.e., $Y_n = I$ with $pBB_y > 0$), or (2) a cumulative damage share (Eq. 7) larger than 0.5 (i.e., 50%) in a 5-year period was subject to stand-replacing disturbance. Non stand-replacing volume damage percentage (vBB) was calculated according to Eq. 8 for every matrix cell. Percentages were converted to area transitions in the matrix (see Fig. 1) accounting for the respective class-width of the volume classes.

$$vBB = \sum_{Y_n \subset I} sBB_{Y_n} \cdot iBB_{Y_n} \quad \text{for } iBB_{Y_n} \leq 0.5 \quad (8)$$

This concept accounts for the chance of more than one damage per 5-year period affecting a certain forest area in a matrix cell. Treating the annual pBB as independent events, however, does not consider increasing damage

potential in successive damage years. More details on the scaling approach as well as a calculation example can be found in Appendix 3.

Model initialisation

The EFISCEN database as used in several European studies (Schröter et al. 2004, Pussinen et al. 2005; EEA 2006; Schelhaas et al. 2006) consists of highly aggregated data from national forest inventories throughout Europe. In our study the initialisation data and model parameters were used from this EFISCEN standard database except where stated otherwise. The spatial scope of the study covered Austria's Norway spruce forests (1.99 Mha), i.e., the full area of potential host trees for *I. typographus* in the country. Data from the fourth Austrian Forest Inventory period (AFI4 1986–1990; Anonymous 1997) was utilised for model initialisation, amended with additional information to allow simulations at finer regional scale.

Whereas the standard EFISCEN dataset for Austria distinguishes eight provinces; this spatial resolution was found to be too coarse and arbitrary with regard to ecological conditions to reflect the countries heterogeneous environmental conditions. This is particularly the case

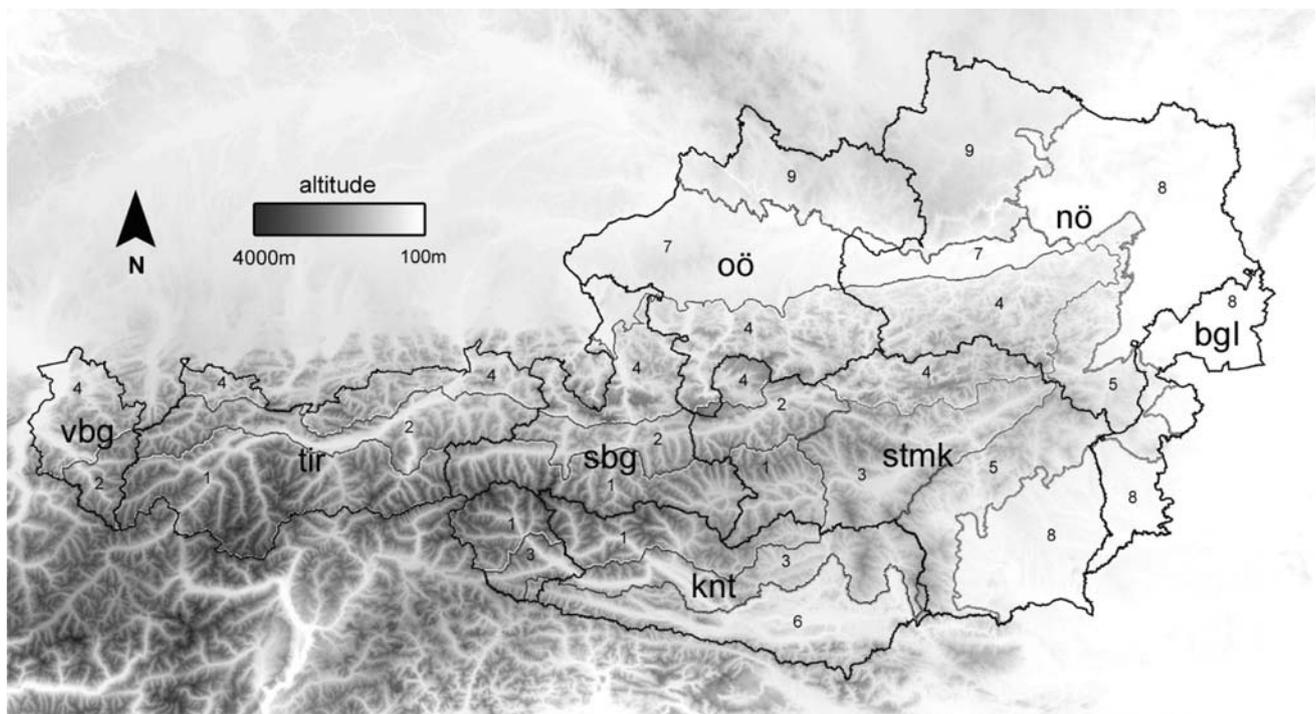


Fig. 2 The spatial resolution of the study consisted of eight federal provinces (*bgl* Burgenland, *knt* Kärnten–Carinthia, *nö* Niederösterreich–Lower Austria, *oö* Oberösterreich–Upper Austria, *sbg* Salzburg, *stmk* Steiermark–Styria, *tir* Tirol–Tyrol, *vbg* Vorarlberg) subdivided into nine ecoregions (1 inner Alps, 2 northern intermediate Alps,

3 eastern intermediate Alps, 4 northern alpine rim, 5 eastern alpine rim, 6 southern alpine rim, 7 northern pre-alpine area, 8 panonic area, 9 Bohemian massif; cf. Kilian et al. 1994), resulting in 31 simulation entities for Austria's Norway spruce forests

since several provinces cover a variety of ecological conditions from lowland pre-alpine areas to the high Alps. Thus, for the current study the provinces were subdivided into ecoregions following Kilian et al. (1994). The intersection of the 8 provinces with the 9 main ecoregions, totalling to 31 simulation entities (see Fig. 2), aimed at balancing the need of a more detailed, ecologically meaningful resolution for the simulations and concerns of increasing uncertainties in applying a large scale scenario model to small entities (see Thürig and Schelhaas 2006).

Extending the default EFISCEN province level database on Austria's forests the forest area distribution over age-classes was compiled for the ecoregions in the provinces utilising Austrian district level information (83 districts, Anonymous 1997). Moreover, since species composition is a highly influential factor with regard to bark beetle susceptibility three mixture classes were distinguished in Norway spruce forests, each being initialised as a separate matrix in EFISCEN. The three classes correspond to the categories reported in Anonymous (1997) and are retained in the design of the damage probability model (see “A statistical meta-model of bark beetle damage”). District level data (Anonymous 1997) were utilised to derive aggregated initial values for the three mixture classes on ecoregion level.

The standard province-level Norway spruce increment functions in EFISCEN were adjusted to represent the contrasting growing conditions of the ecoregions. To that end we used an average site index per ecoregion in the provinces based on Schadauer (1999). Increment functions were fitted to Austrian yield table information (Marschall 1975) and assigned to the simulation entities according to the respective site indices.

Model evaluation

The amended EFISCEN initialisation procedure as well as the new bark beetle disturbance component were evaluated against independent data. First, province level increment, growing stock and age-class distribution as recorded in the fifth and sixth Austrian Forest Inventory periods (AFI5: 1992–1996; AFI6: 2000–2002) were compared against simulated data. Forest management in the evaluation period was prescribed at province level applying the harvest record of the Austrian Forest Inventory. Since salvage from bark beetle damages are implicitly included in these data but are dynamically simulated in this study we deducted the observed amount of bark beetle damages (see below) to derive the level of regular harvest.

Simulated bark beetle damages were evaluated against a 15 year time series of bark beetle damages at province

Table 1 Average temperature and precipitation for the ecoregions^a in the eight federal provinces^b for the evaluation period (1990–2004) and the last decade of the scenario analysis under the climate change scenario (2090–2099)

Province	Ecoregion	Temperature (°C)		Precipitation (mm)	
		1990–2004	2090–2099	1990–2004	2090–2099
bgl	5	9.3	11.4	684	748
	8	9.5	11.7	683	746
knt	1	4.6	7.0	1,099	1,135
	3	5.8	8.2	1,104	1,161
	5	4.5	6.9	1,134	1,205
	6	6.7	9.1	1,169	1,216
nö	4	8.4	10.4	1,072	1,270
	5	8.3	10.4	868	1,011
	7	8.5	10.6	753	846
	8	9.7	11.8	624	729
öö	9	7.9	10.0	765	870
	4	8.2	10.0	1,310	1,453
	7	8.2	10.1	1,095	1,185
sbg	9	7.0	8.9	1,011	1,104
	1	5.0	7.1	1,201	1,171
	2	6.0	8.1	1,299	1,270
	4	7.5	9.5	1,331	1,286
stmk	7	8.6	10.8	1,257	1,207
	1	4.8	6.9	1,028	1,161
	2	6.3	8.3	1,280	1,371
	3	5.9	8.0	1,149	1,264
	4	7.4	9.3	1,416	1,551
tir	5	6.9	9.1	1,044	1,142
	8	9.2	11.3	836	912
	1	4.7	7.0	998	911
	2	6.0	8.3	1,213	1,103
vbg	3	4.4	6.8	1,331	1,199
	4	6.2	8.5	1,285	1,170
	6	3.8	6.2	1,189	1,077
	2	5.6	7.5	1,455	1,308
	4	6.3	8.1	1,795	1,645

^a Ecoregions (cf. Kilian et al. 1994): 1 inner Alps, 2 northern intermediate Alps, 3 eastern intermediate Alps, 4 northern alpine rim, 5 eastern alpine rim, 6 southern alpine rim, 7 northern pre-alpine area, 8 panonic area, 9 Bohemian massif

^b Provinces: *bgl* Burgenland, *knt* Kärnten–Carinthia, *nö* Niederösterreich–Lower Austria, *öö* Oberösterreich–Upper Austria, *sbg* Salzburg, *stmk* Steiermark–Styria, *tir* Tirol–Tyrol, *vbg* Vorarlberg

level (Krehan and Steyrer 2005). Climate data used for the simulation of bark beetle damages (i.e., mean annual temperature and precipitation, cf. Eqs. 4, 5) in the evaluation period were aggregated for the simulation entities (i.e., ecoregions within provinces) from plot level data available for the full set of AFI plots (Lexer et al. 2002).

Average climate conditions for 1990–2004 are given in Table 1 for all combinations of province \times ecoregion.

Scenario analysis

Climate scenarios

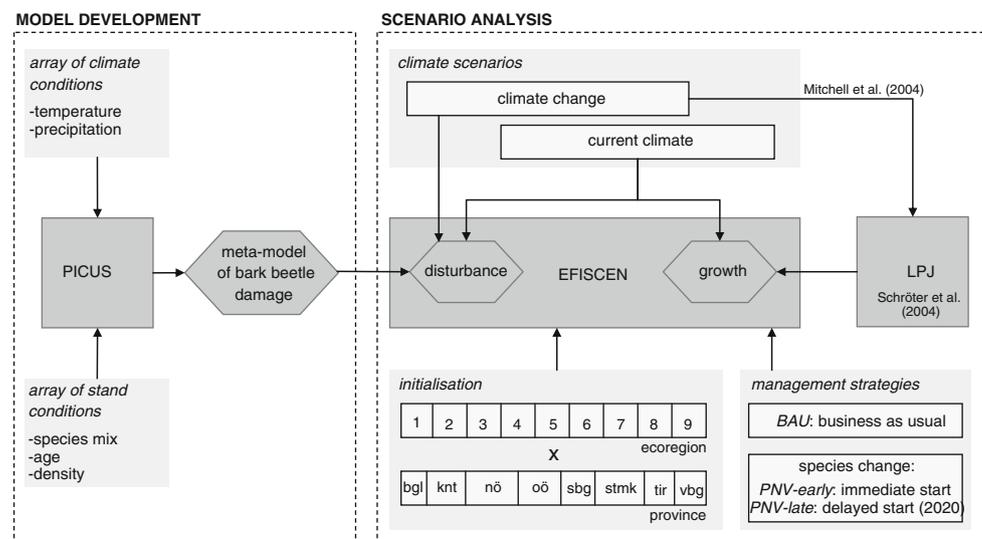
For the period 2005 to 2099 a scenario analysis was conducted, studying the impacts of a climate change scenario on bark beetle disturbances as well as the effects of adaptive management strategies. To analyse the impact of climate change two climate datasets were used: First, a baseline climate scenario was constructed by randomly drawing years from the evaluation period climate series (1990–2004) for the 95-year scenario period. Second, a regionally downscaled transient climate change scenario was simulated (Mitchell et al. 2004). We selected the scenario B2 (IPCC 2000) of the HadCM3 global circulation model as it represents an intermediate trajectory in the scenario envelope provided by Mitchell et al. (2004). The average temperature change for the last decade of the twenty-first century relative to 1990–2004 at country level was $+2.4^{\circ}\text{C}$, precipitation showed only a slight increase at country level ($+20$ mm) with limited decreases and increases in the individual provinces (see Table 1). In order to grant consistency with the evaluation period the anomalies of the climate change scenario were applied to the respective average baseline climate of the ecoregion. Whereas climate drivers were explicitly considered in the approach of simulating bark beetle disturbances the effects on forest growth were considered via an external process model of forest production. For the climate change scenario this growth response had been quantified in a previous study with the process model LPJ (see Schröter et al. 2004).

Management strategies

Three alternative management strategies were studied: Strategy BAU represented business as usual management, implying no species change. Two alternative management strategies investigated a conversion to a species composition close to the potential natural vegetation (PNV) composition (static assessment for current climatic conditions, Kilian et al. 1994). In the absence of coherent large scale adaptation policies such generic strategies are frequently recommended to practitioners to foster ecosystem resilience and decrease risks in forest management (cf. Müller 1994; Leitgeb and Englisch 2006). In the first alternative management strategy the species conversion starts immediately in the simulation (PNV-early), in the second the effect of a delayed management response to climate change is studied by starting species conversion not until 2020 (PNV-late). In both strategies conversion took place only after final felling or stand-replacing disturbance, i.e., young stands were not subject to conversion treatments. Overall, in both alternative strategies the Norway spruce area was reduced to the benefit of beech (*Fagus sylvatica* L.), oak (*Quercus* sp.) and silver fir (*Abies alba* L.), with a focus of conversion activities in pre-alpine regions. Pure Norway spruce forests were only supported in the Inner Alps (ecoregions 1–3), while Norway spruce was fully replaced in ecoregion 8. The management rules for the PNV strategies are described in detail in Appendix 4.

Harvest levels built on earlier studies (cf. Pussinen et al. 2005) and were identical in all simulated management strategies, implying a rise in harvest level until the middle of the twenty-first century ($+23.8\%$ from baseline level) and remaining constant throughout the second half of the

Fig. 3 Overview over the material and models used in the study



century. Due to the shifts in age-class distribution over the scenario period the share of final fellings increased relative to the share of thinnings in the second half of the twenty-first century. Age corridors for final felling differed with ecoregions and tree species, with longer rotation periods in the inner Alps and shorter rotations in prealpine lowlands (final fellings between age 90–200 and 70–110 in ecoregions 1 and 8, respectively for Norway spruce). Figure 3 summarises the main elements of the study.

Study design and analysis

We ran EFISCEN over 110 years (22 5-year simulation periods) where the first 15 years served as evaluation period and the subsequent 95 years were utilised to study the impact of climate change and the effect of changes in management. In the evaluation period, simulations were assessed by comparing model predictions to inventory data from AFI5 and AFI6 (Anonymous 1997, 2002). Due to the irregular inventory intervals simulation results for the comparison to AFI6 were linearly interpolated to 2001 from the model outputs for 1999 and 2004.

In order to compare simulated damage by *I. typographus* to the data of Krehan and Steyrer (2005) the following assumptions were made. Since Krehan and Steyrer (2005) report total bark beetle damages (i.e., including all bark beetle species) the share of *I. typographus* on total bark beetle damages had to be identified.

Estimates of damage by *I. typographus* were available for 4 recent years (Krehan and Steyrer 2004, 2005, 2006) which were averaged and applied for the evaluation period (average *I. typographus* share on total observed bark beetle damages: 81.7%). Furthermore, data in Krehan and Steyrer (2005) are related to damage amounts reported by local forest authorities, i.e., the data correspond to salvaged wood from bark beetle damage. Since the salvage of trees damaged by bark beetle is legally binding in Austria we assumed a salvage level of 95% in the comparison of simulations to observed data.

The scenario analysis conducted from 2005 to 2099 focused mainly on two aspects: the impact of climate change on bark beetle disturbances was quantified by relating the simulated damages in the baseline climate scenario to damages under the climate change scenario. For this comparison both scenarios were simulated under business as usual management. Temporal development and cumulative damage were reviewed at country level as well as at the scale of individual ecoregions. The second main objective in the scenario analysis was to assess the effects of adaptive management strategies. This analysis focused on the potential to confine bark beetle damages by species change and to assess the effect of an early or late start for adaptation (comparison of the strategies PNV-early and PNV-late). Reported timber volumes are given in total stem volume over bark except where indicated (e.g., u.b.m. = merchantable timber volume under bark).

Table 2 Comparison of EFISCEN simulations to Norway spruce forest inventory data (AFI5: 1992–1996; AFI6: 2000–2002) on province^a as well as country (aut) level

Inventory period	Province	Average standing volume stock (m ³ ha ⁻¹)			Average increment (m ³ ha ⁻¹ a ⁻¹)		
		Observed	Predicted	Δ%	Observed	Predicted	Δ%
AFI5	bgl	219.8	208.1	−5.3	10.3	9.5	−7.9
	knt	284.7	292.8	+2.8	8.8	9.4	+7.7
	nö	275.8	289.9	+5.1	8.5	9.4	+10.3
	oö	325.5	337.3	+3.6	10.5	11.3	+7.4
	sbg	325.0	325.1	+0.0	8.5	8.7	+2.7
	stmk	291.1	301.6	+3.6	8.8	9.6	+9.3
	tir	286.5	290.1	+1.3	6.5	6.8	+5.5
	vbg	382.0	342.4	−10.4	7.2	7.5	+3.7
	aut	295.7	303.6	+2.7	8.7	9.3	+7.7
AFI6	bgl	254.7	249.0	−2.2	11.5	10.0	−13.2
	knt	324.3	313.6	−3.3	10.9	10.0	−8.0
	nö	315.6	315.7	+0.0	10.6	9.9	−7.1
	oö	376.3	373.8	−0.7	12.3	11.8	−4.0
	sbg	369.6	343.5	−7.1	9.7	9.2	−4.3
	stmk	331.3	322.5	−2.7	10.4	10.3	−1.0
	tir	326.7	296.5	−9.2	7.7	7.1	−8.2
	vbg	387.2	326.5	−15.7	9.3	7.8	−15.8
	aut	337.0	325.0	−3.5	10.4	9.9	−5.0

^a Provinces: *bgl* Burgenland, *knt* Kärnten–Carinthia, *nö* Niederösterreich–Lower Austria, *oö* Oberösterreich–Upper Austria, *sbg* Salzburg, *stmk* Steiermark–Styria, *tir* Tirol–Tyrol, *vbg* Vorarlberg

Results

Evaluation

Simulated forest development

Between AFI4 (the initial condition for this study) and AFI6 the observed average standing stock in Austria's Norway spruce forests increased by 16.6% from 289.1 to 337.0 $\text{m}^3 \text{ha}^{-1}$ (Anonymous 2002). The corresponding EFISCEN simulation captured this trend, estimating a slightly lower increase in standing stock of 12.4% from 1990 to 2001 (Table 2). Largest deviations between observed and predicted values were found for the province Vorarlberg, which can be related to a considerably different management regime in this province, consisting mainly of continuous cover systems rather than age-class forestry.

The age-class distribution of Austria's spruce forests was found to be strongly skewed towards young age-classes with a distinct peak between age 20 and 40 years in 1990. Whereas this peak even increased in the observations over the available inventory periods EFISCEN simulated a

partly shift to the next age-class (Fig. 4). Possible reasons for this deviation might be a strongly skewed age-distribution within the individual age-classes of the observed forest data, whereas in EFISCEN an even distribution of area within one age-class is assumed. However, the general pattern of the age-class distribution (peak in young forest stands, low share of stands older than 100 years) was consistently retained in the simulation over the evaluation period.

For long-term applications of the model the evaluation of annual increment is of particular relevance since increment is a main driving factor of forest development. EFISCEN showed a slight overestimation of mean annual increment compared to AFI5 (+0.66 $\text{m}^3 \text{ha}^{-1} \text{a}^{-1}$) and underestimated increment relative to the data of AFI6 (−0.52 $\text{m}^3 \text{ha}^{-1} \text{a}^{-1}$). Considering the fact that simulated EFISCEN productivity (empirical, age-dependent growth functions) does not account for periodical climate anomalies the correspondence can be considered satisfactorily. Moreover, the simulated province-level pattern agreed well with the observations, finding increments to be highest in Upper Austria and lowest in Tyrol (Table 2).

Fig. 4 Comparison of inventory and EFISCEN age-class distribution (20-year age-classes; 1 1–20 years, 7 121–140 years, 8 >140 years) for the initialisation (AFI4) as well as for two subsequent forest inventory periods (AFI5: 1992–1996; AFI6: 2000–2002)

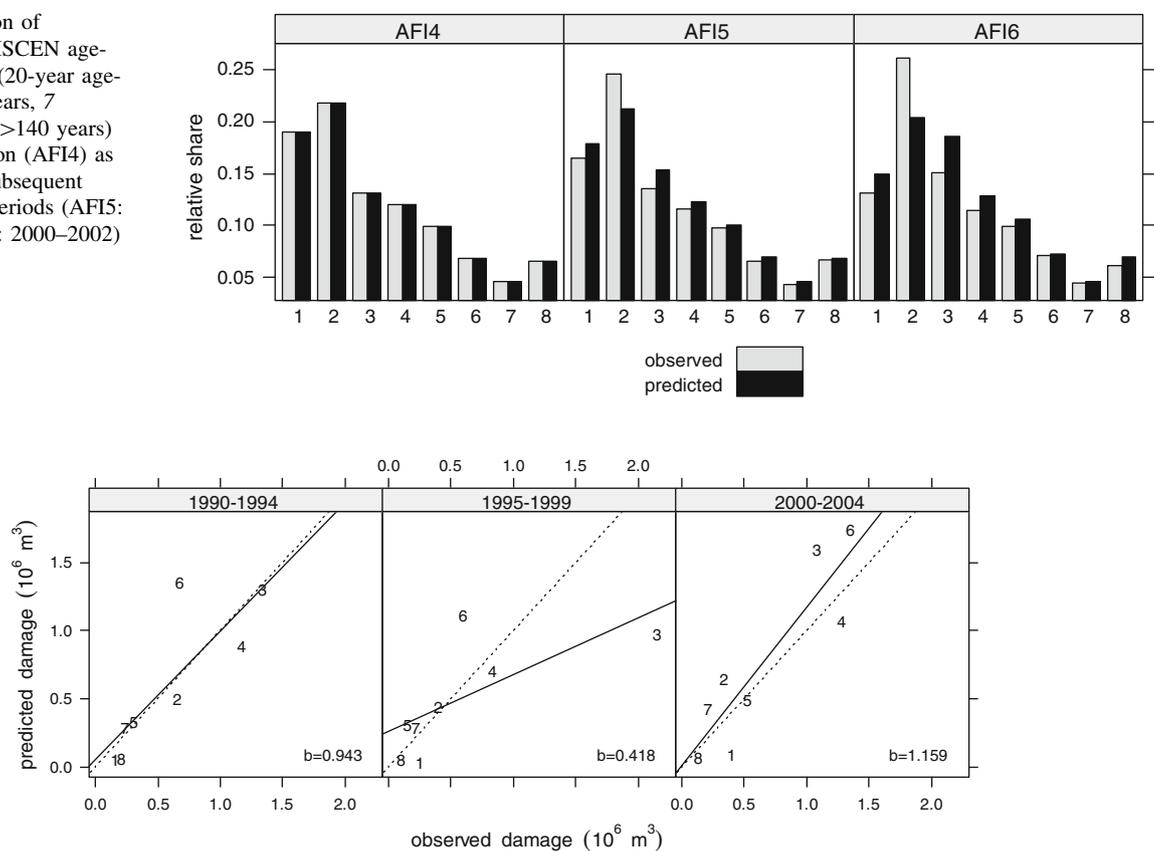


Fig. 5 Observed versus predicted 5-year *Ips typographus* damages for Austria's federal provinces (1 Burgenland, 2 Kärnten–Carinthia, 3 Niederösterreich–Lower Austria, 4 Oberösterreich–Upper Austria, 5 Salzburg, 6 Steiermark–Styria, 7 Tirol–Tyrol, 8 Vorarlberg) in three

evaluation periods (b slope coefficient of the regression model, solid line regression, dashed line 1:1 line). Values are given in salvaged merchantable stemwood under bark

Evaluation of simulated bark beetle damage

Over the 15-year evaluation period the overall simulated damage with EFISCEN (15.11 million cubic metres (Mm^3), salvaged volume u.b.m.) agreed well with the observation (14.71 Mm^3 , salvaged u.b.m.). In the individual 5-year simulation periods, observation and prediction matched well in 1990–1994 (difference +3.2%), bark beetle damage was slightly underestimated in the second and overestimated in the third 5-year period (−14.2 and +17.1%, respectively). The simulations matched well with the pattern of damage in the 15-year period, simulating a decrease in damage from the first to the second simulation period and a significant increase with the highest damages in 2000–2004. At province level, damages simulated with EFISCEN corresponded well to the observations (Fig. 5). In a regression of observed against predicted data the highest coefficient of determination was achieved in 2000–2004 with $R^2 = 0.802$, values for 1990–1994 and 1995–1999 were 0.683 and 0.496, respectively. In the first and the last 5-year period the slopes of the regression analysis were not significantly different from one whereas in 1995–1999 the slope was significantly lower than one ($\alpha = 0.05$). In this period a strong increase in damages in the province Lower Austria was observed. Based on an already high beetle population levels after heavy windthrow events in the early 1990s this rise was triggered by a local snow breakage event in 1995 in combination with non-efficient forest protection measures (Donaubauer et al. 1995, 1996). This local outbreak could not be reproduced by EFISCEN, resulting in a considerable underestimation of damages in Lower Austria in 1995–1999, which exerted a strong leverage on the overall regression results. Reanalysing the intermediate 5-year period omitting the value for Lower Austria resulted in a regression slope of 1.12 (not significantly different from one at $\alpha = 0.05$) and more than 60% of the variance in damages explained ($R^2 = 0.624$). A comparative analysis of relative damage levels (damage percent relative to standing Norway spruce stock) over all provinces in the three 5-year periods resulted in similar coefficients of determination (R^2 from 0.467 to 0.615).

Analysis of climate change impacts and adaptation strategies

Impact of climate change on bark beetle damage

When analysing the impact of climate change on bark beetle disturbances results for the baseline climate and the climate change scenario were compared under business as usual management. Reviewing the temporal pattern of simulated damages over the scenario period 2005 to 2099 (Fig. 6a) it can be seen that already under baseline

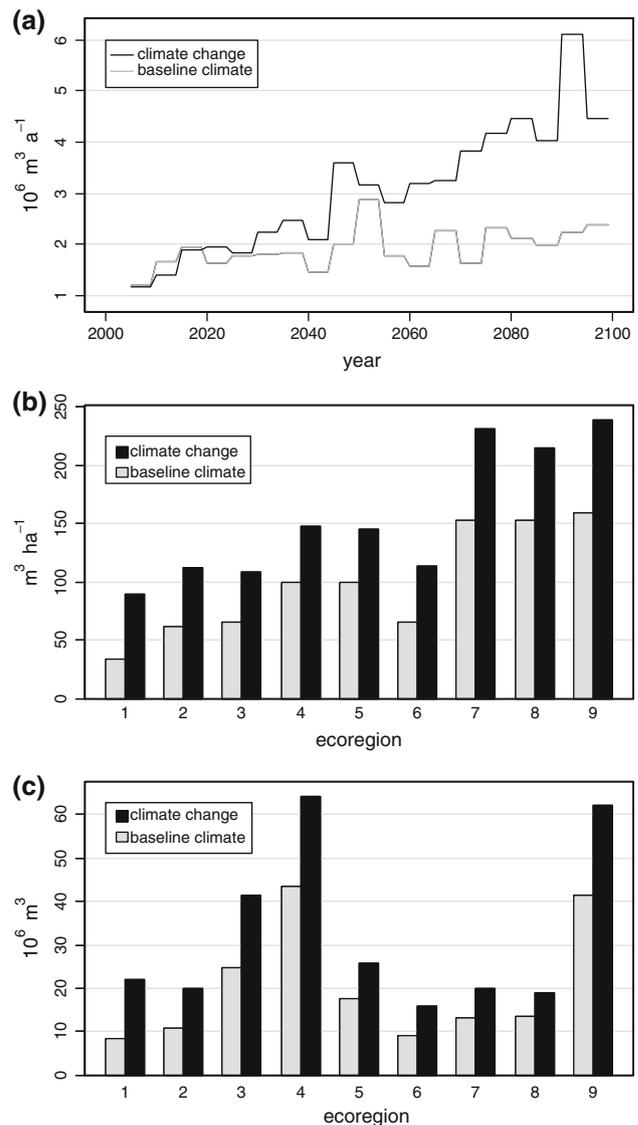


Fig. 6 Temporal development of annual bark beetle damage (a) and spatial distribution of total accumulated bark beetle damages (2005–2099, b and c) under baseline climate and a climate change scenario. Ecoregions range from the Inner Alps (1) to pre-alpine areas (7, 8) and the Bohemian massif (9), see Fig. 2

climate damages increased significantly to more than $2.38 \text{ Mm}^3 \text{ a}^{-1}$ in period 2095–2099 (+79.7% relative to the average damage of the evaluation period 1990–2004). This increase was a result of a considerable change in age-class structure over the twenty-first century, from the current large areas of young Norway spruce stands to higher shares of mature forests highly susceptible to damage by *I. typographus*. Under the climate change scenario damages showed a strong increase over the course of the twenty-first century with simulated damage levels being 3.4 times higher in 2099 than in the evaluation period and reaching a peak of $6.09 \text{ Mm}^3 \text{ a}^{-1}$ (2090–2094; 4.6-fold increase relative to 1990–2004).

Accumulated damage over the 95-year scenario period under climate change was +159% higher than under the baseline climate. Particularly the pre-alpine ecoregions (7, 8, 9) showed very high average damage levels under climate change (Fig. 6b). However, relative increases in total accumulated damage compared to the baseline climate were highest in the alpine ecoregions with the strongest increase in ecoregion 1 (inner Alps, +166%). In total, ecoregion 4 had the highest contribution to accumulated bark beetle damage over the 95-year period (22.4% under the climate change scenario, see Fig. 6c). However, the spatial distribution of total damages changed considerably over the simulation period: In 2005–2009 absolute damages in the alpine ecoregions 1 and 2 were distinctly lower than those of the pre-alpine ecoregions 7 and 8 despite much larger Norway spruce areas in the Alps (ecoregions 1 and 2: 0.55 Mm³; ecoregions 7 and 8: 0.99 Mm³). This relation reversed in the climate change scenario resulting in a considerably higher damage from the two inner alpine ecoregions compared to the two pre-alpine ecoregions in the 2095–2099 (3.59 and 2.63 Mm³, respectively).

Effect of adaptive management strategies

In order to assess potential adaptive management strategies to cope with climate change two alternative variants differing in the onset of adaptation measures were compared to business as usual management. The stand conversion activities in the PNV-strategies resulted in a considerable reduction in Norway spruce area (Fig. 7), however, affecting only young to intermediate age-classes in the simulation period.

Consequently, since young forests are not susceptible to *I. typographus* and old forests were only marginally affected by the conversion management, simulated bark beetle disturbances in the PNV-strategies showed only minor effects in the first part of the scenario period. Overall, the accumulated bark beetle damage over the 95-year scenario period was 7.81 and 2.92 Mm³ lower than under business as usual management in PNV-early and PNV-late, respectively. In line with the design of the conversion strategies (i.e., target species mixture based on the current potential natural vegetation) little to no changes

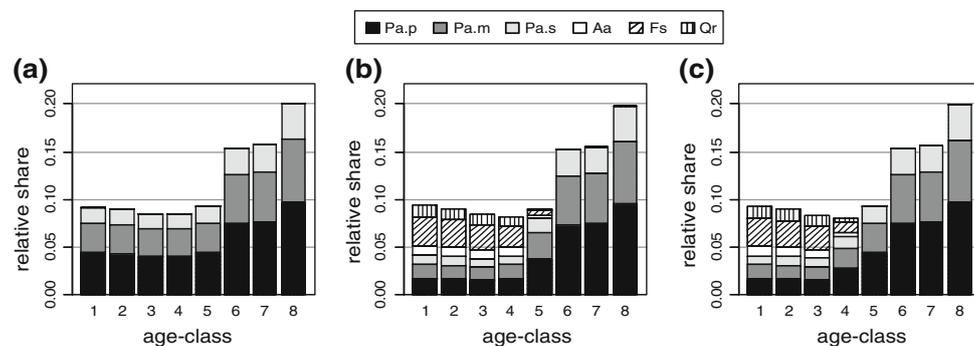


Fig. 7 Tree species composition over age-classes (20-year class width, 1 1–20 years, 7 121–140 years, 8 >140 years) for the year 2099 under the climate change scenario and business as usual management strategy (a) as well as under the species change

strategies PNV-early (b) and PNV-late (c). *Pa.p* pure Norway spruce; *Pa.m* mixed Norway spruce; *Pa.s* only minor Norway spruce share in stand; *Aa* Silver fir; *Fs* beech; *Qr* oak

Table 3 Simulated average damage for the business as usual management (BAU) in the 95-year scenario period and in the last five-year simulation period. Relative changes under the two adaptive management strategies PNV-early and PNV-late are indicated

Ecoregion	Average damage period 2005–2009			Average damage period 2095–2099		
	BAU (m ³ ha ⁻¹)	ΔPNV-early (%)	ΔPNV-late (%)	BAU (m ³ ha ⁻¹)	ΔPNV-early (%)	ΔPNV-late (%)
1	89.19	±0.0	±0.0	7.96	±0.0	±0.0
2	112.45	−0.8	−0.3	9.15	−2.6	−1.2
3	109.13	−1.2	−0.5	9.84	−3.7	−1.8
4	148.19	−3.0	−1.1	11.13	−9.7	−4.6
5	144.87	−3.9	−1.5	11.36	−12.4	−6.2
6	113.47	−4.0	−1.4	9.95	−11.8	−5.5
7	231.07	−4.1	−1.5	15.24	−13.5	−6.8
8	215.21	−6.3	−2.3	14.81	−20.5	−10.3
9	239.60	−2.5	−1.0	15.78	−8.0	−4.2

were simulated for the alpine ecoregions, where Norway spruce is the dominant or co-dominant species in the current natural vegetation composition. The highest overall reduction was simulated in ecoregion 8, where Norway spruce was fully replaced by deciduous species in the conversion strategies. Over the simulation period the effect of delaying the onset of the adaptive management for 15 years (PNV-late) considerably reduced the overall conversion effect on bark beetle damages from -2.69% in PNV-early to -1.01% .

Since long lead times for the effects of the conversion strategies were found in addition to the total accumulated damages over the 95-year scenario period, the period 2095–2099 is reviewed in detail (Table 3). In the last 5-year simulation period the effect of adaptive management was more pronounced due to species changes already affecting age-classes of increased susceptibility to *I. typographus*. From 2095 to 2099, the management strategy PNV-early reduced damages for 1.85 Mm^3 relative to baseline management (-8.3%). PNV-late resulted in a reduction of -4.1% .

Discussion and conclusion

Simulating bark beetle damages in a large scale scenario model

We presented a climate sensitive approach to simulate damage by *I. typographus* in the large scale scenario model EFISCEN by means of a two-stage multivariate meta-model based on extensive stand level model simulations. The particular aim of the approach was to combine information on climate response of beetle development and host resilience with forest structure and composition in ecoregions to cover a broad range of potential interrelationships between climate change and biotic disturbances. The chosen resolution of the simulation approach (federal provinces \times forest ecoregions) was found to balance the needs of detailed information on environmental and stand conditions in heterogeneous landscapes as well as sufficiently large simulation entities for robust predictions of forest development within the EFISCEN matrix framework (cf. Thürig and Schelhaas 2006). The evaluation against forest inventory data showed good agreement between the model and the observations, with EFISCEN being able to simulate the observed increase in standing stock and also capturing observed periodical increment levels. The latter result particularly supported the application of EFISCEN over the extended time horizon of this study (cf. Nabuurs et al. 2000). However, deviances as found for the province Vorarlberg point towards the general limitations of the EFISCEN approach, which is restricted to even-aged

forests managed under an age-class system. The simulation of uneven-aged forestry as practiced in large parts of Vorarlberg's forests and as generally promoted as a promising alternative management option is clearly limited within the current EFISCEN framework.

Furthermore, good correspondence between observed and predicted bark beetle damages at province level was found. Using averaged climate information for ecoregions (2–6 entities per province) EFISCEN including the bark beetle disturbance module was able to accurately reproduce the observed damage levels per province in three consecutive 5-year periods. This result is particularly satisfactory since no overall calibration of the simulation approach was performed to large-scale data sets. Model results were a combination of simulated forest structures in EFISCEN and an upscaling of PICUS model logic on bark beetle damages. The current implementation of bark beetle damages in PICUS was found to suit the requirements for such an upscaling exercise well. Whereas the absence of interannual bark beetle gradations has to be seen as major limitation of the current approach in PICUS (cf. Seidl et al. 2007a), the annually independent calculation fits well for an upscaled application in the EFISCEN environment. Since EFISCEN is a non-spatial model with regard to the distribution of individual forest areas within a matrix cell the simulation of a spatial spread of bark beetle outbreaks as a result of an interannual gradation is generally inhibited by the modelling framework. Such limitations could be overcome by bolstering increased spatial detail in the design of an advanced large scale scenario model.

Furthermore, the approach of utilising annual climate information and aggregate estimated damages to 5-year time steps in EFISCEN was found reasonable in the climate-dependent simulation of bark beetle damages at country scale. Observations show that a time-lag between climate conditions particularly favourable for the beetle and an actual increase in bark beetle damages exists (e.g., Krehan 1993; Tomiczek et al. 2005), which is not accounted for in the annual calculations of damage probability and damage intensity. However, the aggregation of simulated damages to time periods of several years increases the robustness of the approach. It has to be noted that in the evaluation experiment the arbitrary definition of such time periods can have an influence on the fit of observed and simulated data. With that regard the over-estimation in 2000–2004 is somewhat put into perspective by increases in observed bark beetle damages in Austria in 2005, although climate conditions in this year were not particularly favourable for bark beetle development (Krehan and Steyrer 2006). The overall simulated damage over the 15-year evaluation period corresponded very well to the accumulated observed damages with a difference of only $+2.7\%$.

A major limitation of the presented approach is the implicit assumption of an average level of additional breeding material (e.g., wounded trees, fresh standing and downed deadwood) for bark beetles. Essentially, the PICUS bark beetle module relies on the damage data recorded by Lexer (1995), containing outbreaks over a wide range of ecological conditions but in the absence of other disturbance events. Several studies found a considerable impulse to bark beetle gradations from the increasing availability of such highly susceptible breeding material through, for instance, windthrow or snow breakage events (e.g., Schroeder 2001; Eriksson et al. 2005). This limitation is clearly demonstrated for the province of Lower Austria in the evaluation period 1995–1999, where the model was not able to track a dramatic increase in observed damages as a result of a local snow breakage event in 1995 (Donaubauer et al. 1996). Improvements could be made by a direct inclusion of such breeding material which, however, would require temporally accurate prediction of abiotic disturbance events as well as detailed knowledge on deadwood pools suitable for breeding (cf. Göthlin et al. 2000). The meta-model resolution (cf. Appendix 1) implies a further limitation of the approach with regard to potential effects of varying inter-annual climate patterns. Considering these limitations future predictions have to be seen as indicative investigations of the climate-dependencies of the herbivore–host relationship. Since several studies point at the possibility for interannual shifts in e.g., precipitation as well as increases in extreme weather events as storms under climate change (e.g., Leckebusch and Ulbrich 2004) the results presented in the scenario analysis have to be seen as conservative estimates.

Climate change impacts and effects of adaptive management

Simulations of a transient climate change scenario for the twenty-first century resulted in a strong increase of bark beetle damages under business as usual management. At low elevations the simulated damage levels would render sustainable forest management in Norway spruce dominated forests virtually unfeasible. Large shares of these areas (e.g., ecoregions 7 and 8) are already currently under high risk (cf. Krehan 1993; Donaubauer et al. 1996; Tomiczek et al. 1997; Spiecker et al. 2004) and will face increasing pressure under climate change. However, simulation results also showed a particular increase in damages in alpine areas as a result of a strongly extended range of *I. typographus*. Such increasing damage trends at higher altitudes have already been observed in recent years (Krehan and Steyrer 2006) and adumbrate the problems of increased bark beetle damages in alpine terrain (i.e.,

difficult recovery of damaged timber, limitations to the application of conventional forest protection routines in steep terrain). Additional adverse effects associated with such an expansion of biotic disturbances into alpine space are to be expected: For instance, the protective function of forests is of high importance in Alpine areas. In Austria for almost one-fifth of the forest area (Anonymous 2002) protection against soil erosion, avalanches, mudflows or rockfall is the main forest function. Distinct increases in damage under climate change have the potential to hamper a sustainable provision of these forest functions, and thus require a particular focus in the development and implementation of adaptive management strategies for vulnerable areas. Moreover, forests are currently the largest terrestrial C storage in Austria (Weiss et al. 2000). An increase in disturbances as found in this study could impose a negative impact on forest C storages and counteract efforts to climate change mitigation in forestry (cf. Kurz et al. 2008; Seidl et al. 2008).

The preliminary results of this study should be expanded in future works taking the considerable variability in climate predictions into account and investigating additional adaptive management alternatives focusing also on alpine areas. This need is emphasised by the management strategies investigated in this study, which resulted in very limited reduction in bark beetle damage especially in alpine areas. The widespread recommendation to practitioners (e.g., Müller 1994; Leitgeb and Englisch 2006) to aim at a species composition close to the current potential natural vegetation (e.g., PNV strategies based on Kilian et al. 1994) proved inefficient in view of shifting disturbance regimes. A static PNV derived from ecological field classifications is neglecting climate change-induced alterations of ecosystem dynamics. In the context of adaptation targeted conversion to resilient species compositions adapted to future climate conditions is thus necessary (Lindner 2000). A further option to reduce bark beetle damages might be a shortening of rotation periods to reduce particularly susceptible stand development phases (Spiecker 2003).

The importance of proactive management planning explicitly addressing climate change is underlined by the fact that considerable lead-times in positive effects of adaptive management were found in this study. Strategy PNV-early, starting the conversion immediately, resulted in reduced bark beetle damages not before the second half of the century. Moreover, a delay in the onset of adaptive management of 15 years diminished the total effect of PNV-early by –62.4% over the course of one approximate rotation period. Although both adaptive management strategies showed only limited overall reduction potential with regard to bark beetle damage, the effect in the last simulation period indicated the high long-term potential of conversion management. However, additional strategies

should be scrutinised in the future, for instance increasing harvest levels and not limiting conversion to stands subject to final felling in order to achieve higher reduction potentials. Nonetheless, as a prerequisite to implement scenario findings in practical forest management results have to be operational and realistic. With this regard efforts to adapt forest ecosystems to climate change are to be balanced with economical and ecological sustainability under the framework of sustainable forest management.

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Appendix 1: A meta-model of infestation probability

Both the statistical models of infestation probability (Eq. 4, Table 4) and of soil moisture index (Eq. 5, Appendix 2) represent meta-models (cf. Urban et al. 1999) designed to capture the main model behaviour of the stand level model PICUS. It has to be noted that the reported statistics describe the fit of the meta-models to the PICUS simulations rather than to independent observed data. Whereas the stand level model PICUS uses detailed climate information on quasi-daily to monthly time steps aggregated climate parameters (annual integration) were used as explanatory variables in the meta-modelling to assure compatibility with widely available data sets of large spatial coverage. Thus the interannual climate variation is fixed in the meta-model.

The statistical *p*BB model (Eq. 4) showed sensible model behaviour in line with expectations and PICUS model logic. Simulated *p*BB increased with increasing temperature and decreasing precipitation. Furthermore, older stands showed higher probability of bark beetle damage than young stands and the susceptibility to bark beetle increased with increasing host tree share. Decreasing stand densities resulted in slightly increasing probabilities of bark beetle damage in the model, related to increasing light levels in the forest and subsequently increasing bark temperatures. The R^2 for the logit-model was calculated as:

$$R^2 = \frac{1 - (\hat{L}_0/L)^{2/n}}{1 - \hat{L}_0^{2/n}}$$

where n is the number of binary observations and \hat{L}_0 is the maximised likelihood under the null ($R^2 = 0.923$; see Faraway 2006). Average model bias (E) was calculated as an average of errors for all predictions by

$$E = \frac{1}{n} \sum (y_i - \hat{y}_i)$$

where y_i is the observed and \hat{y}_i is the predicted value. The resulting average model bias for the *p*BB model was small ($E = -1.792 \times 10^{-15}$) and not significantly different from zero ($\alpha = 0.05$). Also the mean absolute error of *p*BB, $|E|$,

$$|E| = \frac{1}{n} \sum |y_i - \hat{y}_i|$$

was found to be satisfactorily low with 0.0389. Analysing model residuals over the range of estimation showed no evidence for non-constant residual variation.

Table 4 Parameters for the multivariate logit model of bark beetle infestation probability (Eq. 4)

Predictor	Factor description	Parameter	Standard error
<i>a</i>	Mean annual temperature (logarithmic)	4.234	0.0123
<i>b</i>	Mean annual precipitation (logarithmic)	-1.196	0.00531
<i>c</i>	Stand age	-0.0433	0.000142
<i>d</i>	Stocking density	0.658	0.0249
<i>e</i> (dummy 50%)	Host tree share	-1.425	0.0107
<i>e</i> (dummy 100%)	Host tree share	-2.606	0.0104
<i>a</i> · <i>b</i>	Interaction temperature × precipitation	-0.214	0.00171
<i>a</i> · <i>c</i>	Interaction temperature × stand age	-0.000383	0.0000239
<i>a</i> · <i>d</i>	Interaction temperature × density	-0.0527	0.00417
<i>a</i> · <i>e</i> (dummy 50%)	Interaction temperature × host tree share	0.0993	0.00183
<i>a</i> · <i>e</i> (dummy 100%)	Interaction temperature × host tree share	0.245	0.00178
<i>b</i> · <i>c</i>	Interaction precipitation × stand age	0.00746	0.0000195
<i>b</i> · <i>d</i>	Interaction precipitation × density	-0.104	0.00341
<i>b</i> · <i>e</i> (dummy 50%)	Interaction precipitation × host tree share	0.278	0.00146
<i>b</i> · <i>e</i> (dummy 100%)	Interaction precipitation × host tree share	0.457	0.00143
μ	Intercept	-0.301	0.0371

Appendix 2: A meta-model of soil moisture index

Generalised linear model behaviour was generally in line with the definition of SMI (see Eq. 3), showing a directly proportional relationship between SMI and temperature and an indirectly proportional relationship between SMI and precipitation. However, SMI response to precipitation was found to be widely insensitive to precipitation levels of more than 1,100 mm per year in the PICUS simulations with a strong increase in SMI at lower precipitation levels. Thus, a transformation of the corresponding predictor variable was applied (Eq. 5, Table 5). Nevertheless, the residual distribution showed a slight trend towards an underestimation of low and an overestimation of high SMI values but was, however, not significantly different to the normal distribution around zero. The GLM explained a high proportion of variance in SMI estimates ($R^2 = 0.945$) and average model bias E (2.885×10^{-19}) was not significantly different from zero at $\alpha = 0.05$. Also the mean absolute error of the GLM was small ($|E| = 0.0234$).

Appendix 3: Aggregation of annual damage events to periodic area transitions

To demonstrate the approach of scaling annual damage probabilities to EFISCEN periods we use data of the Burgenland region (bgl) for the period 2001–2005 (baseline climate scenario), 100% host tree share, age class five (80–100 years) and volume class seven ($280\text{--}394 \text{ m}^3 \text{ ha}^{-1}$), see Table 6.

We apply probability theory to account for multiple damages per area unit in aggregating annual meta-model estimates. The joint probability of all independent annual events contained in a subset Y_n , i.e., the area share in the matrix cell damaged $|Y_n|$ times in the years $y \in Y_n$, is represented by $\prod_{y \in Y_n} pBB_y$ (Eq. 6, first term). Since we are

interested in the area damaged only in the years $y \in Y_n$ (and not also in other years of the period), this estimate needs to be corrected for all $Y \subseteq I$ of higher cardinality than $|Y_n|$ containing the elements of Y_n . (Eq. 6, second term, $\prod_{z \in I \setminus Y_n} qBB_z$). Overall $n = 31$ subsets of Y_n exist for $Y \subseteq I$ in a

5-year period $\left(n = \sum_{i=1}^5 \binom{5}{i} \right)$. For $Y_I = I = \{1, 2, 3, 4, 5\}$,

the subset with the maximum cardinality, sBB_{Y_1} represents the area in the EFISCEN matrix cell damaged by bark beetle in all 5 years of the period. In this case the second term in Eq. 6 is an empty set and sBB_{Y_1} is computed as the joint probability of the five damage probabilities, resulting in 4.36×10^{-3} in our example. This area share in the EFISCEN matrix cell is subject to stand replacing disturbance and moved to the bare forest land class. For subset $Y_2 = \{1, 2, 3, 4\}$ the joint probability of 12.34×10^{-3} (Eq. 6, first term) contains also the joint probability for subset Y_1 ($Y_2 \subset Y_1$) and the corrected sBB_{Y_2} is

$$sBB_{Y_2} = \prod_{y=1}^4 pBB_y - \prod_{y=1}^5 pBB_y = \prod_{y \in Y_2} pBB_y \cdot \prod_{z \in I \setminus Y_2} qBB_z$$

(confer the general formulation in Eq. 6), i.e., a value of 7.98×10^{-3} in our example. Applying Eq. 7 the corresponding cumulative damage intensity iBB_{Y_2} is 0.128 and will be treated as non-stand replacing disturbance in the EFISCEN framework ($iBB_{Y_n} \leq 0.5$). Following this sequence for all n subsets of I and applying Eq. 8 results in a volume damage percentage vBB of 5.60% (non-stand replacing) for the 5-year period in our example matrix cell. This percentage is subsequently converted to area transitions to a lower volume class in the EFISCEN matrix framework.

Appendix 4: Species change management regimes based on the current potential natural vegetation composition (PNV)

For the two species change strategies the potential natural species composition for every ecoregion was defined in three elevation belts according to Kilian et al. (1994). Additionally assumptions on the average species composition of the respective natural forest types were made

Table 6 Example meta-model output for annual damage probability (pBB) and damage intensity (iBB) for the years y of a 5-year simulation period in EFISCEN

	Year y in period				
	1	2	3	4	5
pBB	0.467	0.324	0.321	0.254	0.353
iBB	0.0415	0.0330	0.0278	0.0254	0.0319

Table 5 Parameters for the multivariate regression model of soil moisture index (Eq. 5)

Predictor	Factor description	Parameter	Standard error
a	Mean annual temperature	0.00107	0.0000967
b	(Mean annual precipitation) $^{-2}$	25490	574.4
$a \cdot b$	Interaction temperature \times precipitation $^{-2}$	8282	58.93
μ	Intercept	-0.0413	0.000943

Table 7 Distribution of the simulated forest area (i.e., current Norway spruce forest area) to elevation belts and the associated potential natural vegetation^a for the ecoregions as applied for the calculation of conversion area in the PNV scenarios

Ecoregion	Elevation belt (m asl)	Simulated area per ecoregion (%)	Potential natural vegetation composition
1	<900	8.1	Pa, Pa–Ps
	900–1,200	20.0	Pa
	>1,200	71.9	Pa, Pa–Ld, Ld–Pc
2	<900	12.9	Pa–Aa
	900–1,200	29.4	Pa–Aa
	>1,200	57.7	Pa
3	<900	20.2	Pa–Aa, Pa–Aa–Fs
	900–1,200	31.5	Pa–Aa
	>1,200	48.3	Pa
4	<900	45.3	Fs
	900–1,200	31.6	Pa–Aa–Fs
	>1,200	23.1	Pa–Aa–Fs
5	<900	52.9	Qr, Fs
	900–1,200	27.5	Pa–Aa–Fs, Fs
	>1,200	19.6	Pa–Aa–Fs, Pa–Aa
6	<900	39.9	Fs, Qr
	900–1,200	25.9	Pa–Aa–Fs
	>1,200	34.2	Pa–Aa, Fs, Pa
7	<900	93.8	Qr, Fs
	900–1,200	5.4	(Pa)–Aa–Fs
	>1,200	0.8	(Pa)–Aa–Fs
8	<900	77.8	Qr, Fs
	900–1,200	13.3	Fs–(Aa)
	>1,200	8.9	Fs–(Aa)
9	<900	89.6	Qr, Fs
	900–1,200	10.1	Pa–Aa–Fs
	>1,200	0.3	Pa–(Aa–Fs)

Assumed species composition per forest type: Pa–Aa–forest: 50% Pa, 50% Aa; Pa–Aa–Fs–forest: 40% Pa, 30% Aa, 30% Fs; (Pa)–Aa–Fs–forest: 20% Pa, 40% Aa, 40% Fs; Fs–(Aa)–forest: 80% Fs, 20% Aa; Pa–(Aa–Fs)–forest: 70% Pa, 15% Aa, 15% Fs

^a Pa Norway spruce; Aa Silver fir; Ps Scots pine; Ld European larch; Qr oak; Fs beech

(see Table 7). Aggregated with the respective share of the elevation belts on the ecoregion the target species composition (i.e., natural species composition under current conditions) was derived and implemented in the conversion rules (see Table 8). In both PNV strategies Norway spruce forests with a share of less than 30% (category Pa.s, Table 8) were only subject to conversion in areas where Norway spruce is not a dominant species of the potential natural tree species composition (Kilian et al. 1994). If two main forest types had been classified for one elevation belt

Table 8 Species change in the PNV conversion strategies

Ecoregion	Source	Converted to					
		Pa.p	Pa.m	Pa.s	Aa	Fs	Qr
1	Pa.p	100	0.0	0.0	0.0	0.0	0.0
	Pa.m	0.0	100	0.0	0.0	0.0	0.0
	Pa.s	0.0	0.0	100	0.0	0.0	0.0
2	Pa.p	57.6	21.2	0.0	21.2	0.0	0.0
	Pa.m	57.6	21.2	0.0	21.2	0.0	0.0
	Pa.s	0.0	0.0	100	0.0	0.0	0.0
3	Pa.p	48.3	24.8	0.0	23.8	3.1	0.0
	Pa.m	48.3	24.8	0.0	23.8	3.1	0.0
	Pa.s	0.0	0.0	100	0.0	0.0	0.0
4	Pa.p	0.0	21.9	0.0	16.5	61.6	0.0
	Pa.m	0.0	21.9	0.0	16.5	61.6	0.0
	Pa.s	0.0	0.0	54.6	0.0	45.4	0.0
5	Pa.p	0.0	14.3	0.0	11.9	47.3	26.5
	Pa.m	0.0	14.3	0.0	11.9	47.3	26.5
	Pa.s	0.0	0.0	47.0	0.0	26.5	26.5
6	Pa.p	0.0	27.4	0.0	13.5	39.1	20.0
	Pa.m	0.0	27.4	0.0	13.5	39.1	20.0
	Pa.s	0.0	0.0	60.0	0.0	20.0	20.0
7	Pa.p	0.0	1.2	0.0	2.5	49.4	46.9
	Pa.m	0.0	1.2	0.0	2.5	49.4	46.9
	Pa.s	0.0	0.0	6.2	0.0	46.9	46.9
8	Pa.p	0.0	0.0	0.0	4.5	56.6	38.9
	Pa.m	0.0	0.0	0.0	4.5	56.6	38.9
	Pa.s	0.0	0.0	0.0	4.5	56.6	38.9
9	Pa.p	0.0	4.2	0.0	3.1	47.9	44.8
	Pa.m	0.0	4.2	0.0	3.1	47.9	44.8
	Pa.s	0.0	0.0	10.4	0.0	44.8	44.8

The rows gives the source of the area converted (*Pa.p* pure Norway spruce; *Pa.m* mixed Norway spruce; *Pa.s* only minor Norway spruce share in stand) for the ecoregions, columns indicate the species to which the area was converted. Values are given in percent of the area subject to final felling and stand-replacing disturbance in the ecoregion per simulation period

and ecozone in Kilian et al. (1994) we assumed an equal share of both forest types.

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