# The Sensitivity of Central European Mountain Forests to Scenarios of Climatic Change: Methodological Frame for a Large-scale Risk Assessment

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The methodological framework of a large-scale risk assessment for Austrian forests under scenarios of climatic change is presented. A recently developed 3D-patch model is initialized with ground-true soil and vegetation data from sample plots of the Austrian Forest Inventory (AFI). Temperature and precipitation data of the current climate are interpolated from a network of more than 600 weather stations to the sample plots of the AFI. Vegetation development is simulated under current climate ("control run") and under climate change scenarios starting from today's forest composition and structure. Similarity of species composition and accumulated biomass between these two runs at various points in time were used as assessment criteria. An additive preference function which is based on Saaty's AHP is employed to synthesize these criteria to an overall index of the adaptation potential of current forests to a changing climate. The presented methodology is demonstrated for a small sample from the Austrian Forest Inventory. The forest model successfully simulated equilibrium species composition under current climatic conditions spatially explicit in a heterogenous landscape based on ground-true data. At none of the simulated sites an abrupt forest dieback did occur due to climate change impacts. However, substantial changes occured with regard to species composition of the potential natural vegetation (PNV).

# Abbreviations

| | | |
|---|---|---|
| *SMAP* | = | Short- to midterm adaptation potential to a changing climate |
| *LAP* | = | Longterm adaptation potential to a changing climate |
| $ACSMAP_{(i)}$ | = | Assessment criterion (*i*) with regard to *SMAP* |
| $ACLAP_{(j)}$ | = | Assessment criterion (*j*) with regard to *LAP* |
| $P_{ACSMAP(i)}$ | = | Preference function characterizing the contribution of assessment criterion (*i*) to *SMAP* |
| $P_{ACLAP(j)}$ | = | Preference function characterizing the contribution of assessment criterion (*j*) to *LAP* |
| $SWC_m$ | = | Soil water content in month (m) [mm] |
| $AET_m$ | = | Actual evapotranspiration in month (m) [mm] |
| $RO_m$ | = | Runoff in month (m) [mm] |
| $SM_m$ | = | Snow melt in month (m) [mm] |
| *WHC* | = | Water holding capacity of the mineral soil [mm] |
| *SMI* | = | Soil moisture index [0–1] |
| $R_{sm}$ | = | Species response to soil moisture availability |
| $R_n$ | = | Species response to nutrient status of the site |
| $R_{al}$ | = | Tree response to available light |
| $R_{gdd}$ | = | Species response to growing degree days (heat sum > 5.5 °C) |

# 1 Introduction

Central European forests comprise a wide range of ecological site conditions from high altitude coniferous mountain forests to low elevation forests mainly dominated by broadleaved species. In particular mountain forests have to serve a multitude of functions and play an important role in maintaining alpine landscapes. Beyond producing timber these forests protect settlements and infrastructure from natural hazards such as avalanches and rockfall, they prevent soil erosion and play a key role in maintaining biodiversity. The importance of functional sustainable forests has been underlined by a number of international cooperations and resolutions (CIPRA 1997, Ministerial Conference for the Protection of European Forests 1998). Discussions on a likely global climate change gave rise to concerns about possible impacts on forest ecosystems (Houghton et al. 1992).

It is important to recognize that to prevent an immediate loss of forest functioning under changing climatic conditions at least the physiological requirements of trees for the growth segment of their life cycle have to be met. However, to support decision making in forest resource management, information on the synecological be-

haviour of tree species (i.e. the competitive relationships between species) under a changing climate is needed. Short-term experimental studies on physiological processes of small individual saplings are not directly applicable to support decision making on temporal and spatial scales relevant for forest management. Simplistic conceptual models of general altitudinal shifts of vegetation belts with increasing temperatures (e.g. Peters and Darling 1985, Starlinger 1998) are not sufficient to support site-specific silvicultural planning. A promising approach to integrate available knowledge on vegetation-site interactions and to investigate the possible transient responses of forest ecosystems to changing climatic conditions are individual-based models of forest dynamics models (Shugart et al. 1992). A variety of forest models which are considered to be useful for forest management decision support under changing environmental conditions have been developed during the last years. Among existing modelling approaches gap models (patch models sensu Shugart 1998) are considered to be particularly useful for simulating forest development under changing climatic conditions. For European forests such models have been con-

structed by Kienast (1987), Kellomäki et al. (1992), Prentice et al. (1993), Kräuchi (1994) and Bugmann (1994).

Most model applications to assess the potential impacts of climatic change have been confined to a very limited number of scattered sites with more or less synthetic site characteristics (e.g. Kienast and Kuhn 1989, Bugmann 1994). Just recently Lindner et al. (1997) employed two gap models in a regional climate change impact assessment for the State of Brandenburg (Germany) where the site and climate data necessary to initialize the model runs were lumped at a spatial resolution of $10 \times 10$ km$^2$. However, this lumping procedure leads to synthetic "average" site conditions within each gridcell, thus blurring the effect of site characteristics on forest response to a changing climate. In all large-scale model applications so far, the simulations were started from bare ground (i.e. "clear cut conditions") aiming at the steady state species composition as the only assessment endpoint (e.g. Lindner et al. 1997). Despite the obvious relevance of todays forest composition for future forest development very few model-based climate change impact studies considered today's forest composition and structure. One of the rare exemptions was provided by Lindner (1998) who simulated approximately 200 ha of managed forests under a climate change scenario. In a risk assessment Kienast et al. (1996) used the site data available for sample plots of the national forest inventory of Switzerland to feed a static climate-sensitive equilibrium model of the potential natural vegetation. Recently Talkkari and Hypen (1996) presented an outline of the application of gap models based on spatially explicit data for boreal conditions.

So far it can be summarized that most model applications to assess the potential impacts of climate change on alpine forests suffered from the following shortcomings: (i) simulation studies for individual "representative" more or less synthetic site conditions miss the spatial dimension and coverage, (ii) in essentially all model applications simulation runs were started from bare ground, thus neglecting the composition and structure of current forests, (iii) risk assessment studies with static vegetation-site equilibrium models miss the individualistic nature in the

formation of vegetation composition. Furthermore, static equilibrium models are not capable of indicating the transient response of current forests to a changing climate.

To overcome these limitations and to provide an estimate for the sensitivity of current Austrian alpine forests to scenarios of climatic change a modified spatially explicit 3D-patch-model is employed to simulate vegetation development at spatially explicit defined sites. To represent the various combinations of current vegetation and site characteristics and to capture the effects of changing climatic conditions there on, all model runs were initialized spatially explicit with ground-true soil and vegetation data of the Austrian Forest Inventory (AFI).

The objectives of this contribution are threefold: Firstly, we give a comprehensive outline of the employed risk assessment methodology in general. Secondly, the patch model PICUS v1.2 which is used to forecast forest vegetation development is briefly presented, and thirdly, the data required to initialize and to drive the model runs are described. Finally some demonstration results are presented.

# 2 Methods

## 2.1 Risk Assessment Procedures

By definition risk is the chance that an unfavourable event which is related to some kind of damage will occur (Holloway 1979). In case of forests the functioning of forest ecosystems under changing climatic conditions, i.e. the ability of forests to sustainably secure societal needs, is at risk. Regarding climate change impacts the worst case scenario would be a rapid forest dieback. However, impact mechanisms may be more subtle. For instance, in low-elevation forests at the foothills of the Alps secondary coniferous forests mainly consisting of Norway spruce (*Picea abies* (L.) Karst.) may suffer from increased drought which in turn may increase susceptibility to attacks by insects and fungi. This increased vulnerability of forests may result in an imbalance in harvesting operations, thus increasing management costs and causing perturbations of timber markets by imbalancing demand and sup-

ply. Due to the involved complex interactions essentially it is impossible to quantify the conditional probability of a particular event to occur. Rather qualitative risk assessments with aggregated more general risk descriptors are appropriate means (Hunsaker et al. 1990).

A crucial step in risk assessments is the definition of appropriate assessment endpoints (Suter 1993). According to Suter (1993) and Hunsaker et al. (1990) risk assessment endpoints have to meet the requirements of societal and biological relevance, unambiguous operational definition, accessibility to prediction and measurement as well as susceptibility to the hazardous agent. Ecosystem-level characteristics such as species composition or accumulated biomass are considered useful parameters in evaluating the functioning of forests (Grottenthaler and Laatsch 1973, Gundermann 1974, Ott and Schönbächler 1986, Gordon 1994).
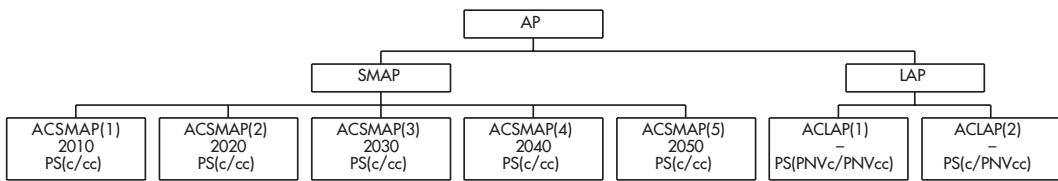
Beyond defining the entity which is at risk (i.e. a forest stand), ecological risk assessment procedures have to devise methods to define the current state and quantify the expected changes of the assessment entities (Suter 1993). Models of forest vegetation development which are responsive to the disturbance agent (i.e. changing climatic conditions) are appropriate means to project ecosystem changes. However, it must be recognized that the fate of a particular forest stand under a changing climate will be hardly ever directly predictable for several reasons:

(a) European forests have been and are subject to intensive forest management. There is no reason to assume that this will change. Thus, knowledge on future silvicultural treatments would be an inevitable prerequisite for such a task. Due to the heterogenous ownership structure in Austria it is neither realistic to assume a single treatment programm for particular stand categories nor to differentiate between all possible stand treatment paradigms.

(b) Stochastic events such as windthrow strongly determine stand development. Such natural disturbances are stochastic events and quite frequent but usually are not included in forest models.

(c) Finally it must be recognized that timber markets are among the main factors driving the selection of stand treatment programms and tree species.

Though there are attempts to link socio-economic timber market models and static vegetation models (Sohngen et al. 2000), these attempts largely miss to take into account the feedbacks between transient forest response to a changing climate (i.e. supply of timber) and timber markets.

Another problem is that the adaptation potential of forests can not be measured directly. Therefore it was concluded that a set of indicators of the adaptation potential of current forests to changing climatic conditions extended over short- to longterm temporal scales can provide a reasonable basis for the evaluation of climate change impacts. One approach very common in central European forestry is to utilize the divergence of the actual forest composition and the species composition of the potential natural vegetation (PNV sensu Tüxen 1956) as a proxy for the suitability of forest vegetation. According to Tüxen (1956) PNV is the equilibrium species composition of the expected forest community at a particular site considering today's site conditions. No direct anthropogenic influences are assumed. The rationale for the use of PNV in resource planning is, that PNV characterizes the ecological potential of forest sites and thus indicates which species mixture is well adapted to the prevailing site conditions (e.g. Kienast et al. 1996). Moreover, minimizing the divergence between PNV and the actual forest composition is expected to minimize the input of effort and energy (i.e. silvicultural treatments) required to sustain ecosystem function (Leibundgut 1981, Mayer 1984). The latter point derives from the fact, that PNV integrates information on the competitive relationships between tree species.

The newly developed patch model PICUS v1.2 (Lexer and Hönninger 1998a, 2000a) was employed to simulate vegetation development under current and future climate starting from current forest composition until the site-specific equilibrium species composition (which is equivalent to PNV) was reached. To allow a future equilibrium species composition to establish the hypothetical future climate of the year 2050 according to a climate change scenario was kept constant with temperatures and precipitation varying around their long-term means. Current forest composition observed at a particular site can

**Fig. 1.** Characterizing the adaptation potential (AP) of current forests to a changing climate by hierarchical decomposition into measurable assessment criteria. – SMAP = short-/midterm adaptation potential, LAP = longterm adaptation potential; PS(c/cc) = percentage similarity (PS) of simulated vegetation under current (c) and changing climate (cc); PS(PNVc/PNVcc) = PS of simulated PNV under current (c) and future climate (cc); PS(c/PNVcc) = PS of current vegetation and simulated future PNV; ACSMAP(*i*) = assessment criterion(*i*) for SMAP; ACLAP(*j*) = assessment criterion (*j*) for LAP.

then be matched with the species composition of this simulated future PNV. Beyond this long-term proxy of tree species suitability biomass accumulation patterns as well as possible abrupt changes in species composition are evaluated on a decenial scale for the period 2000 to 2050 to capture the short- to midterm sensitivity of current forests to a changing climate directly. Fig. 1 shows the hierarchy of assessment criteria used to synthesize an overall index for the adaptation potential of current forests to scenarios of climatic change.

The short- to midterm sensitivity (*SMAP*) of forests to changing climatic conditions was quantified as the difference in species composition and accumulated biomass between the simulated vegetation development under current and changing climate respectively at 10-year-intervals for the period from 2000 to 2050 ($ACSMAP_{(1-5)}$). The forest simulator PICUS v1.2 is run in the PNV-mode, i.e. it is assumed that seeds of all species are potentially available in the simulated stand, no forest management interventions are considered. As an indicator for changes in ecological site potential the divergence of PNV under current and the assumed future climate is calculated ($ACLAP_{(1)}$). Finally the current species set is matched with the equilibrium species composition under the altered climatic conditions of the climate change scenario with regard to the relative abundance of species ($ACLAP_{(2)}$). The latter indicator accounts for the longterm adaptation potential of current forests.

The assessment criteria $ACSMAP_{(i)}$ and

$ACLAP_{(j)}$ were quantified by the percentage similarity PS (Prentice and Helmisaari 1991) (1).

$$PS = 1 - \frac{\sum_{i=1}^{n}|a_i - b_i|}{\sum_{i=1}^{n}(a_i + b_i)} \qquad (1)$$

$a_i$ = proportion (absolute or relative) of species (*i*) in set *a*

$b_i$ = proportion (absolute or relative) of species (*i*) in set *b*

This measure not only evaluates differences in species proportions but also integrates the absolute amount of biomass a species is able to accumulate at a site. PS can take values between 0 (totally different species composition) and 1 (identical species composition).

### 2.1.1 A Multiple-attribute Preference Model to Evaluate the Impact of Climatic Change

To evaluate the overall adaptability of a given stand (i.e. the severity of expected climate change impacts) an approach that borrows from multiple-attribute utility theory (MAUT) was adopted. This method requires the mathematical characterization of preferences over a set of attributes (Goicoechea et al. 1982). According to Fig. 1 the overall utility with regard to the adaptability of a

forest to a climate change scenario is composed of partial utilities with regard to the short- to midterm ($U_{SMAP}$) and the longterm adaptation potential ($U_{LAP}$) respectively (2)

$$U = a \cdot U_{SMAP} + b \cdot U_{LAP} \qquad (2)$$

under the constraint that ($a + b = 1$). The partial utilities are calculated from preference functions $P_{ACSMAP(i)}$ (3a–b) and $P_{ACLAP(j)}$ respectively (4a–b).

$$U_{SMAP} =$$
$$a_1 \cdot P_{ACSMAP1} + a_2 \cdot P_{ACSMAP2} +$$
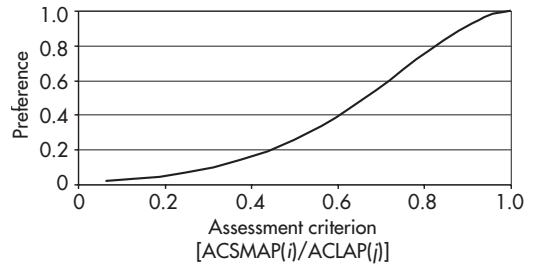$$a_3 \cdot P_{ACSMAP3} + a_4 \cdot P_{ACSMAP4} + \qquad (3a)$$
$$a_5 \cdot P_{ACSMAP5}$$

$$\sum_{i=1}^{5} a_i = 1 \qquad (3b)$$

and

$$U_{LAP} = b_1 \cdot P_{ACLAP1} + b_2 \cdot P_{ACLAP2} \qquad (4a)$$

$$\sum_{j=1}^{2} b_j = 1 \qquad (4b)$$

The preference functions calculate the "value" of each realization of an assessment criterion with respect to its contribution to either *SMAP* or *LAP*. It is important to note, that it is not very realistic to assume a linear relationship between the similarity of vegetation under current climate and a climate change scenario and its meaning with regard to forest adaptability. The preference functions in (3a) and (4a) were estimated by the eigenvalue method as applied in the analytic hierarchy process (Saaty 1977, 1996). Essentially the approach of Saaty requires a priori knowledge of all elements to be compared. However, the assessment criteria can take any value between 0 and 1. Thus, the original method of Saaty had to be modified. Instead of comparing already realized outcomes for a criterion we partitioned the entire possible range for a criterion (0–1) in eight categories of equal width and used the midpoints of these categories as elements in the comparison matrix. The resulting priorities from the matrix were scaled to 1. Thus, we ar-
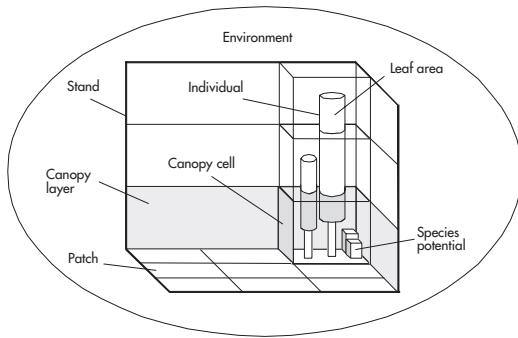


**Fig. 2.** Continuous preference function for the valuation of ACSMAP$_{(i)}$ and ACLAP$_{(j)}$.

rived at a continuous normalized preference function which subsequently could be employed to calculate preference values for any realization of *ACSMAP*$_{(i)}$ and *ACLAP*$_{(j)}$, respectively (compare Fig. 2).

## 2.2 The Forest Model

In this section a brief outline of PICUS v1.2 is given. For details see Lexer and Hönninger (1998a, 2000a). Conceptually, PICUS v1.2 is based on the following assumptions: (a) a 3-dimensional spatial resolution of $10 \times 10 \times 5$ m is sufficient to track spatial effects such as influence of gap size and orientation and allows for the application of distance independent algorithms to model inter-tree competition, (b) the consideration of light, of the thermal regime represented by an effective temperature sum, of soil moisture availability and of site nutrient status provides a reliable description of a species' fundamental niche. In addition winter minimum temperatures are evaluated twofold with respect to regeneration processes: regarding frost damage as well as chilling requirements to induce dormancy and subsequently break of flower buds (Sykes et al. 1996). (c) Optimum unconstrained tree growth can be derived from data on open grown trees (OGTs).

The $10 \times 10 \times 5$ m structural base elements contain all information on the distribution of tree biomass in space. From this point of view PICUS is a descendant of the ZELIG-model (Urban 1990). A similar approach can also be found in Huth et al. (1996). Thus, unlike in conventional gap models which in fact can be considered as
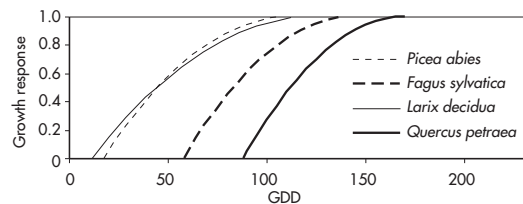
**Fig. 3.** Spatial structure of PICUS v1.2.

"point"- models, the simulated forest changes over time as an interactive unit rather than as a series of independent plots. Because PICUS includes a fairly detailed model of the above- and within-canopy light regime interactions among neighbouring patches as well as the effect of slope and orientation on incoming radiation are considered. Moreover, it allows to differentiate the light conditions at different sites with respect to shielding effects of surrounding topography. The range of spatial interactions between patches depends on the characteristics of the vegetation on the simulated patches (i.e. tree height, crown length), site characteristics (slope, orientation, latitude) and season (i.e. solar altitude, sun angle and direction). The spatial core structure of the model is presented schematically in Fig. 3.

As in most gap models actual tree growth in PICUS is derived from a growth potential which is modified by environmental constraints. Optimum diameter increment is derived from the carbon budget approach given by Moore (1989). Beyond diameter at breast height (1.3 m) tree dimensions are defined by tree height, height to the live crown and leaf weight and leaf area, respectively. Tree height is updated by means of a species specific second order polynomial function. Leaf weight and leaf area are calculated from dbh for species groups adopting the recently refined equations from Bugmann (1994). Leaf weight is distributed equally along the bole. Determination of the height to the live crown is based upon species-specific light requirements (light compensation point) and the radiation regime a tree experiences.

## Tree Response to Environmental Factors

An index of available light for an individual tree is calculated from the available light a tree crown in the simulated stand actually experiences. The response to available light for 9 species categories is modelled by interpolating between the response functions for category 1 "very shade tolerant" and category 9 "very shade intolerant".

The representation of the thermal environment basically follows other recent gap models where a heat sum above the threshold for positive net photosynthesis (GDD) and winter minimum temperatures (WT) are used to represent the temperature regime at a site. GDD are meant to characterize general thermal conditions for photosynthesis (Larcher 1995), WT may seriously limit the regeneration of tree species which are vulnerable to frost occurrence (Woodward 1987, Ellenberg 1996). The coldest month of a year is taken as an estimate for WT (Bugmann, 1994) and is also used to evaluate, whether the chilling requirements for species requiring dormancy are satisfied (Sykes et al. 1996). It is important to note that in PICUS tree growth is not restricted at super-optimal temperatures. Based on the consideration that tree growth at a species' southern range limit is not necessarily constrained by temperature per se (compare Bugmann and Solomon 2000) we modified the heavily criticized parabola (e.g. Schenk, 1996) and derived new temperature response functions from the combined network of forest inventory data, soil and meteorological data (Lexer and Hönninger 1998b). In Fig. 4 these newly formulated temperature response functions are presented for selected species.



**Fig. 4.** Modified temperature response functions for selected species (Lexer and Hönninger, 2000). GDD = Heat sum above the threshold for positive net photosynthesis.

To provide a more realistic representation of soil water dynamics we modified the one layer bucket model which is conventionally used in gap models (e.g. Pastor and Post 1985, Kienast 1987, Bugmann 1994). The general logic to update the state variable soil water content ($SWC$) each month is given by (5)

$$SWC_{m+1} =$$
$$SWC_m + P_m + SM_m - AET_m - RO_m \qquad (5)$$

where input of water to the soil is given by precipitation ($P$) and snowmelt ($SM$). Actual evapotranspiration ($AET$) and runoff ($RO$) represent output of water from the soil. $RO$ occures, if $SWC$ exceeds the water holding capacity of the soil ($WHC$). $SM$ is calculated as a function of temperature according to Dunne and Leopold (1978). $AET_m$ represents the monthly proportion of the atmospheric evaporative demand ($PET_m$) that can be satisfied by available soil water. An estimate for $PET_m$ is computed applying the formulation of Thornthwaite and Mather (1957). Given unlimited water supply $AET$ equals $PET$. When the soil moisture content decreases, $PET$ is modulated depending on soil texture and the amount of water in the soil (6).

$$AET_m = PET_m \cdot f_s\left(\frac{SWC_m}{WHC}\right) \qquad (6)$$

Formulations $f_s$ for different soil texture types were taken from Dunne and Leopold (1978). To provide a parameterized representation of the simultaneous processes of water infiltrating into the soil and water being depleted from the soil input and output from the bucket were calculated in 3 time steps per month where the sequence of water input and output varies stochastically. The ratio of evaporative demand and supply integrated over the growing season is considered a reliable proxy of drought stress experienced by vegetation (7).

$$SMI = 1 - \frac{\sum\limits_{bgs}^{egs} AET}{\sum\limits_{bgs}^{egs} PET} \qquad (7)$$

$bgs$ = begin of growing season (temperature exceeds 5.5 °C)

$egs$ = end of growing season (temperatures below 5.5 °C)

Similar to the derivation of the temperature response the data of the Austrian Forest Inventory were utilized to derive soil moisture response functions. PICUS v1.2 requires monthly temperature and precipitation data. The model driving climate can be provided as either time series data or can be sampled stochastically from empirical distributions fitted to longterm time series of climate data. A normal distribution is used for generating monthly temperatures, whereas a 2-parameter gamma distribution is used for precipitation.

In contrast to other gap models PICUS v1.2 doesn't rely on the nitrogen supply function as presented by Pastor and Post (1985). Instead the water holding capacity at a site ($WHC$), the pH-value (PH) as well as the C/N-ratio (CN) of the top soil are employed to characterize the nutrient status of a site. In a fuzzy logic control unit these indicators of site nutrient status are linked to tree growth performance by means of a rule base. Rules were constructed for each of four response categories (tolerant, intolerant, PH-sensitive, CN-sensitive). By linear interpolation between these four main response categories a total of 9 species response groups were defined. Based on ecological literature (e.g. Ellenberg, 1996) each species was assigned to one of these response categories. A detailed description is given in Lexer et al. (2000).

In modelling the combined effect of environmental factors on tree growth various approaches have been proposed. Following Liebig's law of the minimum Botkin et al. (1972) and Kienast (1987) employed the minimum-operator to derive the aggregate environmental response from an array of monocausal responses. In Botkin (1993) the multiplicative combination of all environmental factors was used. Bugmann (1994) proposed a geometric mean which implicitly considers compensation between environmental factors. In PICUS v1.2 compensation as well as intensification was considered explicitly. The belowground factors soil moisture ($R_{sm}$) and nutrient supply ($R_n$) were combined in $R_{soil}$. The hypothesized interrelationship of $R_{sm}$ and $R_n$ was made explicit by (8)–(10).

$$R_{soil} = R_{biom} \cdot f_{soil}(R_{sm}, R_n; 0.3) \qquad (8)$$

$$effect = \frac{0.3 \cdot (\max(R_{sm}, R_n) - 0.5)}{0.5} \qquad (9)$$

$$fsoil =$$

$$\begin{cases} \min\left[R_{max}, R_{min} + (R_{max} - R_{min}) \cdot effect\right]; effect > 0.0 \\ \min\left[R_{min}, R_{min} + (R_{min} - R_{min} \cdot R_{max}) \cdot effect; else \right] \end{cases}$$

$$(10)$$

$$R_{min} = \min(R_{sm}, R_n)$$
$$R_{max} = \max(R_{sm}, R_n)$$

Thus, if both the effects of soil moisture and nutrient supply are below 0.5, the effect of the most limiting factor is intensified. If one environmental factor satisfies species requirements with $R_{max}$ 0.5, the effect of the limiting factor could partly be compensated. The combined effect of $R_{sm}$ and $R_n$ was further intensified by $_{biom}$ which decreases with increasing accumulated biomass at the simulated patches as a function of the maximum possible biomass. Based on the approach of Fischlin et al. (1995) site-specific estimates of maximum biomass were calculated from temperature, an index of soil water availability and an index for site nutrient status. In a similar approach the effects of temperature ($R_{gdd}$) and light ($R_{al}$) were combined. The final overall response to environmental factors was calculated from the combined below and aboveground effects again utilizing the compensation algorithm from eqs. 8–10.

Similar to other patch models, tree mortality is modelled as a stochastic process. The intrinsic risk of death is increased under unfavourable conditions when a tree fails to realize a specified minimum diameter increment for a number of successive years. This approach is conceptually based on a hierarchical pattern of carbon allocation where diameter increment is of low priority and thus an indicator of reduced tree vigor (Kozlowski et al. 1991). For *Picea abies* bark beetle mortality is considered explicitly by coupling the patch model with a 2-stage-stand risk model (Lexer and Hönninger 1998a).

New trees are generated by a recruitment submodel and are explicitly modelled beyond a diameter treshold of 1.0 cm ± 0.2 cm. In contrast to other patch models PICUS considers seed pro-duction by overstorey trees and seed dispersal explicitly. The seed production of each adult tree is modelled as a function of tree size, the species' seed production characteristics and current light consumption of the parent tree. Seed dispersal of each seed producing tree is modelled as a cone-shaped density function around the center of each parent tree's patch where the cone is defined by tree height and maximum dispersal range. For selected species zoochorous seed dispersal is considered as well. PICUS v1.2 was already successfully evaluated against spatially explicit expert reconstructions of PNV along ecological gradients in the Eastern Alps (Lexer and Hönninger 2000a, Lexer and Hönninger 2000b).

## 2.3 Model Input and Initialization

### 2.3.1 Site Data

To utilize available data and to further enhance the information content of existing data bases the study at hand was based on the sampling grid of the Austrian Forest Inventory (AFI). AFI samples site and vegetation data on a systematic 3.89 km grid of permanent plots. At each grid location a cluster of four plots is located at the vertices of a 200 m square. For this risk assessment a subsample of all AFI-plots was taken which is considered to represent the variety of site-vegetation combinations of Austria's forests. For each plot included in the risk assessment study an array of site and soil parameters was required to initialize the model runs (Table 1). Geographical location, aspect as well as slope are standard site descriptors recorded by the Austrian Forest Inventory (AFI). The surrounding superelevated topography in the four main directions (horizon) was retrieved from a digital elevation model of 250 m spatial resolution implemented in GIS ARC/Info. Lack of quantitative soil data is a weak point of many large-scale forest inventories. To circumvent this problem Lexer and Hönninger (1998c) and Lexer et al. (1999) developed a routine for the estimation of soil parameters for sample plots of the AFI based on Bayesian probability theory. This approach was employed to calculate estimates for the soil

**Table 1.** Site and soil parameters required to initialize the simulation runs with PICUS v1.2.

| Parameter | Unit | Characterization |
|---|---|---|
| Coordinates | (°, ', ") | Location of site |
| Aspect | (°) | Eight categories |
| Slope | (%) | Inclination of slope |
| Horizon (1, 2, 3, 4) | (°) | Angle to horizont in directions north, east, south, west |
| Water holding capacity | (cm) | Uppermost 30 cm mineral soil |
| ph-value | – | Average of the uppermost 30 cm mineral soil |
| C/N-ratio | – | Average of the uppermost 30 cm mineral soil |

parameters WHC, PH and CN for all sites included in the impact study.

### 2.3.2 Vegetation Data

At each sample plot of the AFI vegetation data is recorded. Using variable radius plot sampling (Bitterlich 1948) with a basal area factor of 4 m²/ha trees larger than 10.4 cm in diameter are recorded at least by dbh and species. All trees with diameters between 5 and 10.4 cm are recorded on a fixed area plot located at the plot center with a radius of 2.6 m. No trees smaller than 5 cm diameter are sampled. From this information a species specific diameter distribution was generated for each selected sample plot. The spatial resolution of PICUS would allow for the consideration of horizontal species mixture patterns. However, AFI does not provide sufficient information on this stand characteristic. Thus, trees larger than 5 cm in dbh were assigned randomly to the patches of the simulated forest starting from the largest diameter class. Tree height and leaf weight were calculated by the model-internal relationships. The initial height to the live crown was determined by calculating the light regime in the initialized stand with the radiation submodel of PICUS. Initial leaf weight below the light compensation point of a species was pruned.

Established regeneration at a site requires particular consideration as it provides the potential next generation of trees. Unfortunately AFI provides just semiquantitative information on the regeneration status at a sample plot (Instruktionen für die Feldarbeit der ... 1995). For AFI a minimum number of seedlings is required depending on the average height of the seedlings (minimum height = 10 cm) to proceed with data collection. Thus, plots with existing sparse regeneration might occur in the data records with the label "no regeneration". From the attributes which are subsequently recorded three AFI-parameters were utilized for the current study to quantify the regeneration status at a sample plot: (i) the distribution of seedlings (categories: whole area, in groups, single), (ii) for a maximum of five species the percent cover (crown projection area) of the dominating height class of a species (6 categories) as well as (iii) the mixture type of that species (categories: pure, groups, random). From the cover percentages the number of seedlings per hectar was calculated with (11)

$$a = x \cdot d_c \tag{11}$$

where $a$ is the average distance between neighbouring seedlings, $d_c$ is the average crown diameter of a species of a given height class and $x$ is a constant specific of a cover perentage class as given in Instruktionen für die Feldarbeit der ... (1995). The species specific crown diameters for given heights were calculated from formulae in Hasenauer (1997). Once the average distance $a_{(i)}$ between neighbouring individuals of a species is known, the expected number of seedlings ($n_{(i)}$/ha) was calculated from (12) assuming a triangular tree distribution.

$$n_{(i)} / ha = \frac{10000}{\dfrac{a_{(i)}^2 \cdot \sqrt{3}}{4} \cdot 6} \tag{12}$$

With this approach a pool of available seedlings at a site was calculated and provided as input to PICUS. Recruitment of new trees in PICUS draws on this seedling pool as long as seedlings are available. Seedling numbers in the pool are either reduced by the recruitment process or by unfavourable environmental conditions characterized by the environmental drivers of PICUS (see section 2.2).

### 2.3.3 Climate Data

For the risk assessment we required current climate and climate change scenarios at all selected AFI-plots. Current climate at the plots was derived from a network of more than 600 weather stations. For this purpose Austria was divided into 8 subregions (compare Tabony 1985). A subregion is comprised by a valley system with borders running along mountain ridges. Thus, it should be guaranteed that most of the subregion share the same air mass with more or less the same vertical temperature distribution. Temperature was supposed to show no significant horizontal gradients within one subregion so that a single vertical temperature–altitude relationship could be deduced using data from all available weather stations within a subregion. Temperature values for each point of interest are calculated with this polynomial temperature–altitude relationship for each individual month and subregion with the elevation of the point as input. In a subsequent step this temperature values are then modified with regard to topography (aspect, slope, horizon) utilizing the ratio of incoming shortwave radiation at the particular point and incoming radiation under the assumption of a flat horizon and zero slope. A more detailed approach was applied to the spatial interpolation of precipitation. For each AFI- plot per individual month a precipitation–altitude relationship was deduced fitting a linear model to the precipitation of the nearest 20 weather stations (Lauscher 1976). With this model residuals for each of the 20 weather stations were calculated and a residual was interpolated for the point of interest by an inverse distance weighting procedure. With the point-specific residual, the precipitation–altitude relationship and the altitude of the point of interest a precipitation value can then be recalculated for each AFI-plot.

For the present study it is planned to derive transient climate change scenarios for AFI sample plots from simulation runs of the global circulation model ECHAM4 under several scenarios of the IPCC (Houghton et al. 1992). Since the spatial resolution of general circulation models (GCMs) is too coarse to directly derive reliable regional climate change projections statistical downscaling methods (e.g. Gyalistras et al. 1994)

are applied. Currently empirical orthogonal functions (EOF) are tested to establish statistical relationships between the behaviour of the meteorological fields for temperature and humidity at the grid points of the NCAR data set extending from 1961 to 1995 and time series of monthly mean temperature and precipitation at the sample plots of the AFI. In a further step this relationship will then be used to deduce climate change effects from GCM-output.

For a first application of the developed risk assessment procedure we defined a climate change scenario in accordance with average anomalies at GCM gridpoints over central Europe. With regard to the year 2050 we assumed winter temperature to linearly increase by 2 °C, summer temperatures by 2.5 °C. Precipitation during summer was reduced by 15 percent. Similar assumptions had been made in earlier impact studies (Bugmann 1994, Kienast et al. 1996).

## 5 Applying the Methodology: An Example

The described risk assessment methodology is demonstrated for a small number of sites located in the ecoregion 4.2 (northern front range of the Alps, eastern part) according to Kilian et al. (1994). This ecoregion covers an altitudinal range of approximately 2000 m, thus including a variety of forest types from oak-hornbeam forests at low elevations to subalpine spruce forests. Fifteen sample plots were randomly drawn from this AFI subset (Table 2). PICUS v1.2 was run under current climate as well as under the defined climate change scenario for 1000 years each. This period was sufficient to reach equilibrium species composition. Size of the simulated forest was 1.0 ha. Model output was stored every 10 years to increase computation speed. The comparison of simulated steady state species composition under current climate with the expected PNV as reconstructed by vegetation experts yielded very plausible results (Table 3). This comparison was based on quantitative characterizations of PNV-formations with regard to possible ranges of species proportions for each of the 23 considered forest communities (Table 4). The 15

**Table 2.** Site characteristics, soil and general climate parameters for selected sample plots of the AFI in ecoregion 4.2 (Kilian et al. 1994).

| ID | Altitude (m) | Aspect (°) | Slope (%) | WHC (cm) | PH | CN | $T_{av}$ (°C) | $Prec_{av}$ (mm) |
|----|------|------|------|------|-----|------|------|------|
| 246 | 1050 | 0   | 64 | 10.8 | 7.2 | 21.5 | 5.6 | 1393 |
| 252 | 950  | 45  | 90 | 19.8 | 3.7 | 17.1 | 6.1 | 1405 |
| 304 | 750  | 0   | 30 | 17.6 | 7.1 | 15.6 | 6.9 | 1439 |
| 319 | 1250 | 0   | 72 | 12.9 | 6.4 | 13.5 | 4.8 | 1604 |
| 258 | 850  | 270 | 8  | 34.3 | 3.9 | 16.3 | 5.7 | 1323 |
| 361 | 1050 | 270 | 16 | 21.1 | 5.1 | 18.9 | 5.6 | 1542 |
| 441 | 450  | 180 | 39 | 14.5 | 4.4 | 10.2 | 7.9 | 919 |
| 491 | 450  | 180 | 12 | 22.6 | 5.3 | 13.4 | 7.9 | 713 |
| 458 | 650  | 180 | 30 | 12.7 | 6.9 | 17.1 | 6.9 | 930 |
| 482 | 350  | 0   | 19 | 12.6 | 4.4 | 15.0 | 8.5 | 780 |
| 492 | 350  | 0   | 0  | 15.6 | 4.0 | 14.5 | 8.5 | 683 |
| 407 | 1350 | 0   | 61 | 12.8 | 4.4 | 12.0 | 4.2 | 1302 |
| 445 | 1650 | 45  | 45 | 9.1  | 5.8 | 12.7 | 2.9 | 1227 |
| 377 | 950  | 135 | 35 | 17.1 | 4.0 | 18.3 | 5.6 | 1001 |
| 437 | 850  | 270 | 65 | 14.3 | 7.2 | 20.3 | 6.1 | 1175 |

**Table 3.** Comparison of simulated and expert PNV at selected sample plots of the Austrian Forest Inventory. Simulated equilibrium species composition classified according to Starlinger (unpublished).

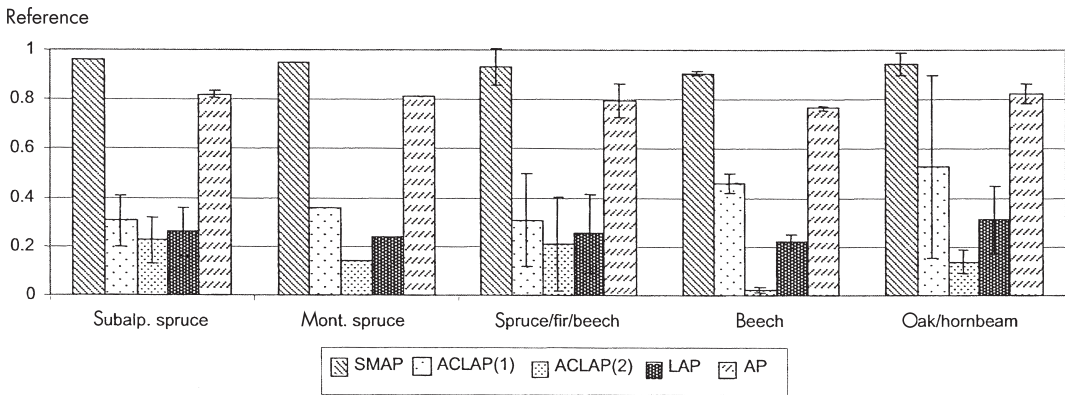| Expert PNV at AFI-plots (code) | Simulated equilibrium species composition | | | | |
|---|---|---|---|---|---|
| | Subalpine spruce forest | Montane spruce forest | Spruce/fir/beech forest | Beech forest | Oak/hornbeam forest |
| Subalpine spruce forest (03) | 2 | – | – | – | – |
| Montane spruce forest (04) | – | – | 1 | – | – |
| Spruce/fir/beech forest (06) | – | 2 | 5 | – | – |
| Beech forest (07) | – | – | – | 1 | 1 |
| Oak/hornbeam forest (08) | – | – | – | 1 | 2 |

**Table 4.** Examples for the quantitative characterization of possible species proportions for natural forest communities (PNV). Source: (Starlinger, unpublished).

| Expert PNV | Code | Possible species proportions* |
|---|---|---|
| Larch/stone pine forest | 01 | (ld+pc)  0.6, pc  0.15, pa < 0.35, aba < 0.15, ps < 0.05, acp < 0.05, sum of other species  0.1 |
| Spruce/fir forest | 05 | (pa+aba) > 0.5, aba  0.15, ld < 0.4, ps < 0.35, (acp+fs+fe+ug+ainc) < 0.2, qusp < 0.1, sum of other species < 0.1 |

* ld = *Larix decidua*, pc = *Pinus cembra*, pa = *Picea abies*, aba = *Abies alba*, ps = *Pinus sylvestris*, acp = *Acer pseudoplananus*, fs = *Fagus sylvatica*, fe = *Fraxinus excelsior*, ug = *Ulmus glabra*, ainc = *Alnus incana*, qusp = *Quercus* spp.

selected plots covered the whole range from subalpine and montane spruce forests (2 plots and 1 plot respectively), mixed spruce-fir-beech forests (7 plots), beech forests (2 plots) to oak-hornbeam forests (3 plots). Compared to other gap model evaluations this test can be considered rather restrictive and thus strengthened our confidence in the reliability of model results. It

Reference



**Fig. 5.** Selected assessment criteria and indices for the adaptation potential of current forests grouped by forest types (current climate). – Data base: 15 sample plots of the Austrian Forest Inventory.

is important to note that PICUS v1.2 also performed reasonably well at other temperate forest sites all over Europe (Badeck et al., in preparation). Thus, it can be concluded that the model realistically captures synecology of European tree species and is not primarily tuned to the sites included in this study. In Fig. 5 selected assessment criteria which had been calculated from the model output as well as the aggregated indices for the adaptation potential are presented by forest types under current climate. From the figures for *SMAP* it can be seen that obviously at none of the 15 sites an abrupt forest dieback did occur due to the changing climate. However, the assessment criterion $ACLAP_{(1)}$ which characterizes shifts in *PNV* under a changed climate indicates, that major changes in the ecological site potential are about to occur under the applied climate change scenario. It is interesting to note, that at least for the 15 selected sites this change seems to be more severe at higher altitudes. This may indicate that at the oak/hornbeam sites the drought tolerance limits of these species had not been reached yet whereas at high elevation sites increasing temperatures favoured the immigration of species with higher temperature requirements. Matching current species composition with future *PNV* ($ACLAP_{(2)}$) yields generally low preference values regarding the longterm adaptation potential (*LAP*) with similar values for all forest types indicating a rather low longterm adaptation potential. Due to the high weight of the short- to midterm index *SMAP* in eq. (2) the overall rating for all 15 stands is fairly high with the lowest values occuring at today's beech sites. This surely is due to the substantial portion of planted Norway spruce at these sites which are outcompeted by broadleaves under a warmer and drier climate, whereas the index *AP* at oak/hornbeam sites yields higher values due to the fact that at these sites current forests mainly consist of broadleave-dominated stands which are less affected by a changing climate.

# 6 Discussion

In this paper a risk assessment methodology for Austrian forests is presented. Core of the approach is the application of a recently developed 3D-patch model at sample plots of the Austrian Forest Inventory. The main argument for this approach origines from the fact that large-scale forest inventories which are installed in many European countries provide unique georeferenced data on forest vegetation composition and structure. To complete the set of site attributes necessary to initialize and drive forest simulation models selected physical and chemical soil parameters had been estimated by means of empirical probabilistic relationships (Lexer and Hönninger 1998c, Lexer et al. 1999). Current climate data on a monthly basis were interpolated from more than 600 weather stations. In the presented demonstration application of the risk assessment system a general increase of temperature and a

decrease in summer precipitation respectively had been assumed. This rather crude assumption will be replaced by transient climate change scenarios which will be derived from GCM-output by statistical downscaling techniques. The integrated data base of site, vegetation and climate data allows for representative sampling procedures of the multi-dimensional space of site/vegetation combinations.

In a first demonstration of the methodology it could be shown that PICUS v1.2 was able to realistically reproduce equilibrium species compositions at spatially explicit sites in the heterogenous landscape of the Eastern Alps. It is important to note that simulated *PNV* was compared to another – expert based – model of *PNV*. Nevertheless, the results of this comparison in combination with the modifications in model formulations strengthened our confidence in model reliability. The criticized parabolic temperature response included in earlier patch models (e.g. Bugmann 1994, Kräuchi 1994) has been replaced by an asymptotic response function which was parameterized based on a broad empirical data base (compare Lexer and Hönninger 1998b). Thus, in PICUS v1.2 trees are potentially able to grow well beyond their natural geographical range limits. This leads to a much more realistic model behaviour of PICUS compared to earlier models. For instance, Norway spruce has been heavily promoted at sites naturally supporting broadleaved forest communities. A parabolic response to temperature parameterized from natural range limits would result in unrealistic forest dieback events in such secondary spruce forests. Nevertheless, despite this modification PICUS v1.2 simulates broadleaved forest types at today's beech and oak sites due to the modelled competitive characteristics of tree species. Thus, we are confident that at least for the range of temperatures covered in the present study model behaviour has been improved. However, we admit that the problem of defining the fundamental niche of tree species remains a highly relevant problem (e.g. Austin 1992).

In contrast to other climate change impact studies we employed an approach from the field of multiple-attribute utility theory to synthesize a set of indicators of forest sensitivity to changing climatic conditions to an overall index for the adaptation potential of current forests. The advantages of this approach are twofold. Firstly, through the modification of Saaty's method it was possible to calculate consistent preference values for any realization of the employed assessment criteria with regard to the adaptation potential of forests. Thus, we avoided abrupt and often not very plausible discontinuities which often occur if discrete risk rating matrices are employed (e.g. Kienast et al. 1996, Grabherr et al. 1998). Another advantage of the presented approach is, that it allows sensitivity testing with regard to the subjective judgements involved in calculating the relative importance of individual assessment criteria. With the employed approach it is possible to capture the transient response of currently existing forests to scenarios of climatic change. A decenial sequence of anomalies in composition and biomass accumulation under current climate and a climate change scenario is condensed to an indicator for the short- to midterm adaptation potential of current forests. No human interventions are assumed. The latter assumption may seem unduly when dealing with managed forests. However, this "no management" assumption is a prerequisite to identify forest conditions vulnerable to a changing climate. Species compositions which are well adapted to the evolving site conditions will show no signs of abrupt diebacks and rather maintain forest functions without management interventions. This natural behaviour of forests would be blurred by the effect of simulated management operations. The "classical" approach in Central European silviculture to derive the suitability of tree species at a given site by utilizing the species composition of the potential natural vegetation (*PNV* sensu Tüxen 1956) as a benchmark is employed to derive an estimate of a "longterm" adaptation potential of current forests (compare Kienast et al. 1996). In accordance with Kienast et al. (1996) this approach alone would provide a rather crude classification of a current forest's risk in case of climatic change because absence of naturally dominating tree species may not result in a forest breakdown. However, the greater the shift in the ecological site potential and the larger the divergence between current species composition the more likely is an adverse effect of climatic change on forest functioning or the more intense the required management to maintain forest func-

tions. It is important to note that with the presented approach the current forest is matched with PNV which is generated by a dynamic vegetation model for each site specifically. Thus, the postulation of fixed species proportions for syntaxonomic PNV-formations (e.g. Mucina et al. 1993, Ellenberg 1996) was avoided.

There are two important points to be adressed when interpreting the results from the demonstration example. Firstly, it is important to recognize the uncertainties involved with climate change scenarios. Driving an ecosystem model with a climate change scenario by definition will result in a scenario of forest ecosystem development. In addition there is no reason to assume that climate change will come to a halt in 2050. Secondly, several sources of uncertainty in the employed forest model have to be considered (model structure, model parameters) when interpreting simulation results. From this we might conclude that climate change impact studies do not have predictive value but rather are sensitivity tests of how a forest ecosystem might respond under a range of specified conditions which may never occur in reality (Bugmann 1997).

The described methodology will be applied to an extensive sample of plots from the Austrian Forest Inventory to represent the various vegetation-site combinations of Austrias forests. The presented methodology seems particularly suitable to adress the first task of the "classical" sequence of problem solving (Rauscher 1999): problem identification. Based on such findings management strategies can then be developed to mitigate the possible impacts of a changing climate.

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