# Adaptation options to reduce climate change vulnerability of sustainable forest management in the Austrian Alps

**Rupert Seidl, Werner Rammer, and Manfred J. Lexer**

**Abstract:** Sustaining forest ecosystem functions and services under climate change is a major challenge for forest management. While conceptual advances of adapting coupled social–ecological systems to environmental changes have been made recently, good practice examples at the operational level still remain rare. The current study presents the development of adaptation options for 164 550 ha of commercial forests under the stewardship of the Austrian Federal Forests (AFF). We used a comprehensive vulnerability assessment as analysis framework, employing ecosystem modeling and multicriteria decision analysis in a participatory approach with forest planers of the AFF. An assessment of the vulnerability of multiple ecosystem goods and services under current management served as the starting point for the development of adaptation options. Measures found to successfully reduce vulnerability include the promotion of mixed stands of species well adapted to emerging environmental conditions, silvicultural techniques fostering complexity, and increased management intensity. Assessment results for a wide range of site and stand conditions, stand treatment programs, and future climate scenarios were used to condense robust recommendations for adapting the management guidelines currently used by AFF practitioners. Overall, our results highlight the importance of timely adaptation to sustain forest goods and services and document the respective potential of silvicultural measures.

**Résumé :** Le maintien des fonctions et services de l'écosystème forestier malgré le changement climatique représente un défi majeur pour l'aménagement forestier. Bien que des progrès conceptuels pour adapter les systèmes socio-écologiques combinés aux changements environnementaux aient été accomplis récemment, les exemples de bonnes pratiques à l'échelle opérationnelle sont encore rares. Cette étude présente le développement d'options d'adaptation pour 164 550 ha de forêts commerciales gérées par l'entreprise « Austrian Federal Forests » (AFF). Nous avons utilisé une évaluation poussée de vulnérabilité comme cadre d'analyse en ayant recours à la modélisation écosystémique et à l'analyse de décision multicritère dans une approche participative avec les gestionnaires forestiers de l'AFF. Une évaluation de la vulnérabilité des multiples biens et services de l'écosystème dans le cadre de l'aménagement actuel a servi de point de départ pour le développement d'options d'adaptation. Les mesures capables de réduire la vulnérabilité incluent la promotion des peuplements mélangés avec des essences bien adaptées aux conditions environnementales émergentes, les techniques sylvicoles qui favorisent la complexité et un aménagement plus intensif. Les résultats de l'évaluation pour une large gamme de stations et de conditions de peuplement, de programmes de traitement des peuplements et de scénarios climatiques futurs ont servi à formuler des recommandations robustes pour adapter les lignes directrices d'aménagement actuellement utilisées par les praticiens de l'AFF. Dans l'ensemble, nos résultats font ressortir l'importance d'une adaptation opportune pour maintenir les biens et services de la forêt et documenter le potentiel des différentes interventions sylvicoles.

[Traduit par la Rédaction]



## Introduction

Climate change is one of the biggest challenges of the coming decades, threatening to exceed the planetary boundaries of a save operating space for humanity (Rockström et al. 2009). Consequently, climate change is at the center of attention of science and policy, with a major focus on mitigating the anthropogenic interference with the climate system (IPCC 2007). Yet it becomes increasingly clear that alongside intensified mitigation efforts, adaptation will be necessary to cope with the already inevitable adverse effects of climate change. The analysis of Stern (2006), for instance, highlights the economic importance and potential of adaptation measures in tackling climate change. Timely adaptation is of particular relevance in forestry, due to the longevity of forest ecosystems and the extensive lead times of management effects.

Forest management paradigms have undergone drastic changes over the last decades, and emerging concepts such

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as ecosystem management and sustainable forest management (SFM) are increasingly adopted in the stewardship of forest ecosystems (see Kohm and Franklin 1997; MCPFE 2003). These concepts inter alia advocate a science-based decision-making process and a continuous evaluation and adaptation of management in the light of emerging scientific understanding, as well as shifting societal objectives. Recent scientific efforts to bolster SFM have focused on embracing multiple forest functions and services beyond timber production (e.g., Keeton 2006; Seidl et al. 2007*a*), on integrating emerging ecological understanding (e.g., Palik et al. 2002; Kimmins 2008), and on accommodating a revived societal interest in forest ecosystems (e.g., Mendoza and Prabhu 2000; Spies and Duncan 2009). Increasingly, the need for an explicit consideration of a changing environment within SFM is recognized (Spittlehouse 2005; Ogden and Innes 2007).

Vulnerability assessment is one methodological approach to do so, measuring the degree to which a community or a resource may be affected by adverse effects of climate change (Füssel and Klein 2006). In acknowledging ecological as well as socioeconomic dimensions of climate change, the vulnerability concept is congruent with the post-normal, "wicked" decision problems that are common in managing ecosystems (cf. Rauscher 1999; Turner et al. 2003). Pioneering work at large scales demonstrated the application of vulnerability assessment approaches in the context of ecosystem services (Schröter et al. 2005), and recent conceptual work led to the development of general adaptation frameworks in forestry (e.g., Maciver and Wheaton 2005; Spittlehouse 2005; Millar et al. 2007; Heinimann 2010). Nitschke and Innes (2008), for instance, recently applied a vulnerability assessment framework in the context of forest management planning in British Columbia, Canada, adapting forest zoning with regard to changing fire risk. For Central Europe, where small-scale structures (i.e., fragmented, densely populated landscapes, small-scale ownerships) often limit the feasibility of segregating objectives in designated zones, a multipurpose approach to forestry is proposed under the umbrella of SFM (MCPFE 2003). Previous work in the region focused on the assessment of predetermined alternative management strategies under conditions of climate change (e.g., Fürstenau et al. 2007; Seidl et al. 2008). Coherent adaptation strategies that are explicitly deduced from comprehensive climate change assessment frameworks and embrace the multitude of forest goods and services under SFM are still rare. Good practice examples for planning and decision making under climate change — addressing the complex reality of forest management — would, however, be of high value in facilitating a diffusion of climate change adaptation theory into practical management (Heinimann 2010).

The current study, conducted in cooperation with the Austrian Federal Forests (AFF), focused on 164 550 ha of commercially managed forests distributed over Austria, ranging from lowland to subalpine forest types in the Eastern Alps. A recent assessment, assuming continuation of current management, identified these forests as substantially vulnerable to climate change (Seidl et al. 2011). Consequently, our objectives here were (*i*) to identify operational stand- and site-specific climate change adaptation measures that are able to reduce vulnerability, i.e., ensure a sustainable provision of ecosystem goods and services (as specified by AFF decision makers and stakeholders) also under climate change, and based on this bottom-up assessment, (*ii*) to deduce general recommendations for climate change adaptation to amend and update the current management guidelines for AFF practitioners.

## Material and methods

### Study design

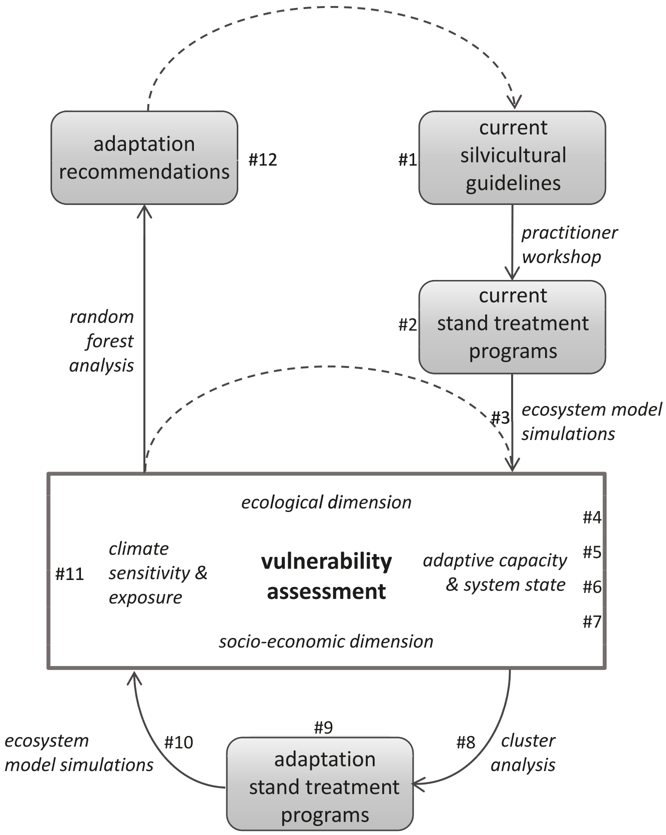
We harnessed ecosystem modeling and multicriteria decision analysis (MCDA) in a participatory approach — including a dialogue with stakeholders of the AFF, as well as a close cooperation with AFF decision makers — towards the aim of developing climate change adaptation guidelines for practical forest management. To operationally address adaptation, we distinguished two decision-making levels in forest management: (*i*) the level of silvicultural guidelines (SIG), issued by the AFF strategic planning team and used as the framework for decision making by practitioners, and (*ii*) the level of actual stand treatment programs (STP) for specific representative stand types. Starting from the current AFF management guidelines (Weinfurter 2004), we translated their SIG into operational silvicultural treatment programs for representative stand-level planning units to be able to address climate–management interactions with high fidelity. Vulnerability assessment, and the subsequent derivation of adaptation options, was conducted for a large variety of these planning units, accounting for the heterogeneity in site and stand conditions in the complex terrain of the Eastern Alps. Finally, we used the results of this fine-grained assessment to synthesize adaptation recommendations in a bottom-up manner (Fig. 1). The main steps of our approach are summarized in Table 1, and the subsequent descriptions of Methods and materials follow this sequence.

### Starting points: current management and expected exposure to climate change

The AFF silvicultural guidelines (Weinfurter 2004), constituting the major planning instrument of the current AFF management strategy, were used as the starting point for the study (cSIG). These guidelines contain target tree species compositions and related rotation lengths, as well as tending and thinning regimes for a variety of planning units, and form the main reference for operational management decisions by AFF foresters. Weinfurter (2004) defines planning units as unique combinations of site type (i.e., soil type, soil depth, bedrock) × ecoregion × elevation belt (for descriptions of the latter two categories, see Kilian et al. 1994). For the current study, the AFF selected 52 planning units representing 164 550 (noncontiguous) hectares of commercially managed forests. Five of these entities were on calcareous bedrock, and two each were on crystalline and flysch substrate. Quantitative soil information was available from the database of Seidl et al. (2009*a*).

As baseline climate for every planning unit, a representative climate record for the period 1961–1990 was selected from a regular grid of interpolated weather station data (monthly resolution) for Austria's forests (Lexer et al. 2002). These 30-year time series were detrended and extended to a 100-year climate baseline by randomly sampling annual records. Baseline climate conditions reflect the wide climatic

**Fig. 1.** Overview of the approach to derive climate change adaptation recommendations for the current management guidelines of the Austrian Federal Forests (AFF). Numbers 1 to 12 indicate the analysis steps as described in Table 1.




gradient covered by the study area, ranging from mean annual temperatures of 2.2 °C (subalpine elevation belt) to 8.8 °C (colline elevation belt), with a mean annual precipitation range from 707 to 1665 mm (for details, see Lexer and Seidl 2009).

To account for uncertainties in climate change exposure, three climate change scenarios were employed, corresponding to the A1B, A2, and B1 storylines of the IPCC (2000). Climate anomalies (unforced vs. scenario conditions) were derived from ECHAM 5 global circulation model runs for the IPCC 4th Assessment Report (Roeckner et al. 2006). Anomalies were imposed on baseline climatology to obtain a consistent set of climate scenarios per planning unit. All three climate change scenarios predict a steady warming throughout the 21st century, with average temperature lapse rates ranging from +0.282 °C (B1) to +0.505 °C (A2) per decade (average over the study region). Annual precipitation levels differ only marginally from baseline in all climate change scenarios. However, interannual precipitation patterns shift towards drier summer periods in all three scenarios (mean decrease in precipitation in June, July, and August between –18.0% and –27.3% in scenarios B1 and A1, respectively).

## Operational stand treatment programs

For an operational assessment of the current SFM strategy, the general guidelines in Weinfurter (2004) required translation into stand treatment programs for actual combinations of planning units × stand types (cSTP, see step 2 in Table 1). Two different target species compositions were selected per planning unit by the AFF planning team to account for variability in species distribution and AFF management goals on planning units. Among them, forest types dominated by Norway spruce (*Picea abies* (L.) Karst.) were most abundant (69.2% of the represented forest area). Mixed forest types accounted for 28.5%, while deciduous forest types of European beech (*Fagus sylvatica* L.) and oak (*Quercus petraea* L. and *Quercus robur* L.) were chosen as management targets on 2.3% of the study area.

A workshop with field staff of the AFF helped to break down this information into operational stand treatment programs (cSTP) for the selected planning units and target species compositions. The majority of cSTP were even-aged age-class systems with a median rotation age of 120 years. A typical stand treatment program consisted of two to three selective thinnings from above in the first half of the rotation and an additional light thinning from below in later stand development stages. Depending on the regeneration system, final harvesting was conducted as clear cut (usually <2 ha in size) followed by planting, or as shelterwood cut with natural regeneration. In line with the Austrian forest legislation, trees killed by natural disturbances were salvaged immediately.

## Projections of future forest development

Stand treatment programs were implemented into the simulation environment of a forest ecosystem model, and forest development was projected over the 21st century under different climate scenarios (step 3 in Table 1). To control for age-class effects, every target species composition and its respective stand treatment program was simulated twice for every planning unit, starting from two different generic development stages as initial conditions (i.e., a young pole stage, quadratic mean diameter ~15 cm, and a timber stage, quadratic mean diameter ~35 cm). Data from AFF forest inventory plots were used to derive the information needed for the generation of these generic initial conditions (e.g., diameter distributions, height curves). In summary, stand treatment programs for four stand types (i.e., two target species compositions and two initial stand development stages) were investigated for every planning unit under four different climate scenarios over 100 years (i.e., 52 × 4 × 4 = 832 unique assessed cases).

The tool employed to project dynamic interactions between climate change, management, stand structure, and composition was the ecosystem model PICUS v1.41 (hereafter referred to as PICUS). PICUS is a hybrid forest gap model (Seidl et al. 2005) combining a three-dimensional (3D) gap model approach (Lexer and Hönninger 2001) with a physiologically based production approach (Landsberg and Waring 1997). The model simulates individual tree dynamics on 10 × 10 m gaps and was applied in this study on a generic 1 ha basis. It accounts for spatially explicit interactions between trees via a 3D light module, simulates seed dispersal explicitly (Lexer and Hönninger 2001), and incorporates ecosystem carbon, nitrogen, and water cycles. It features a forest management module, as well as a detailed submodel of bark beetle induced tree mortality (Seidl et al. 2007*b*). PICUS has been evaluated for the Eastern Alps by Seidl et al. (2005) and has recently been successfully applied in the context of

**Table 1.** Analysis steps to derive climate change adaptation options for sustainable forest management based on a comprehensive vulnerability assessment framework. Note that the latter, serving as the core of our analysis (steps 3 through 7), is also described in detail in Seidl et al. (2011).

| No. | Task and description | Drivers and information | Level |
|---|---|---|---|
| 1 | Review current SFM strategy | Guidelines by Weinfurter (2004) | SIG |
| 2 | Deduce representative operational stand treatment programs | Based on step 1, workshop with AFF field staff | STP |
| 3 | Project future forest development with the ecosystem model PICUS v1.4 | Initial site and stand conditions; climate scenarios; stand treatment programs (step 2) | STP |
| 4 | Generate values for vulnerability indicators representing the SFM system | Data from step 3, see Tables 1 and 2 for indicators in the vulnerability dimensions sensitivity and state | STP |
| 5 | Evaluate indicators at a dimensionless scale: sensitivity (SE): {–1, …, +1}; state (ST): {0, …, 1} | Data from step 4, common indicator thresholds and categories as defined by the AFF strategic management planning team, PROMETHEE preference functions for SE indicators, direct valuation for ST indicators | STP |
| 6 | Aggregate the respective standardized indicator values to scores for the vulnerability dimensions sensitivity and state | Data from step 5, indicator weights representing the relative importance of management objectives as defined by the AFF strategic management planning team | STP |
| 7 | Map the assessed planning units on the vulnerability surface for analysis and comparison | Data from step 6, vulnerability classes following Seidl et al. (2011) | STP |
| 8 | Find vulnerability patterns (i.e., temporal, indicators affected) | Use data from steps 5, 6, and 7 in a cluster analysis | STP |
| 9 | Develop adaptation measures tailored to reduce vulnerability | Based on clusters from step 8, with input from AFF practitioners and strategic management planning team | STP |
| 10 | Project future forest development with adaptation measures implemented (ecosystem model PICUS v1.4) | Initial site and stand conditions; climate scenarios; adapted stand treatment programs from step 9 | STP |
| 11 | Evaluate residual vulnerability, i.e., the vulnerability remaining with adaptation measures implemented | Re-run analysis steps 4 through 7 using data from step 10 as input | STP |
| 12 | Deduce recommendations for "climate-smart" (i.e., low vulnerability) management guidelines from the analysis of stand treatment programs | Analyze and aggregate results from steps 7 and 11 by means of data mining with Random Forests to deduce recommended adaptations to Weinfurter (2004) (step 1) | SIG |

**Note:** SIG, silvicultural guidelines; STP, stand treatment program.



climate change and decision support in the region (e.g., Seidl et al. 2008).

Stand treatment programs were implemented in the simulation as demonstrated by Seidl et al. (2007*a*), generally prescribing a fixed sequence of management interventions for every entity in the assessment. However, dynamic adaptive behavior was accounted for by means of an extended rule base in relation to emerging stand development, for instance, triggering premature final harvesting and afforestation in cases where simulated cumulative bark beetle damages led to a disintegration of stands.

### Vulnerability indicators of sustainable forest management

The core of the study was a vulnerability assessment framework based on a vulnerability surface approach (Luers 2005). It was designed to allow quantitative comparisons of different ecosystems and management alternatives with regard to their climate change vulnerability and thus is well suited to serve as a tool in developing options for adaptation (cf. Füssel and Klein 2006; Seidl et al. 2011). Following Luers (2005), the orthogonal dimensions of the vulnerability surface, which are informed by vulnerability indicators, were defined as (*i*) climate change sensitivity and exposure (SE) (i.e., a response to changes in climate), and (*ii*) climate-mediated state with regard to system-inherent thresholds (ST) (i.e., a measure of adaptive capacity of the system).

Climate change vulnerability indicators for the dimensions SE and ST were derived from a set of criteria and indicators for SFM in Austria (MCPFE 2003; Anonymous 2008; see step 4 in Table 1). A stakeholder panel, including representatives of the AFF, the World Wildlife Fund Austria, and the University of Natural Resources and Applied Life Sciences (BOKU), was instrumental in identifying important issues and selecting relevant vulnerability indicators (see also Niedermair et al. 2007). The final vulnerability indicator set included productivity, timber and C stocks, biodiversity, disturbances, ecophysiological tree species suitability (i.e., the position within a species' fundamental niche space), silvicultural flexibility, and cost intensity of management. The first five indicators are sensitivity indicators (Table 2), i.e., their differential performance under baseline climate and climate change conditions was evaluated. Decreasing indicator values were generally associated with increasing climate change vulnerability, with the exception of disturbance indicators, for which a positive relationship with vulnerability was assumed (i.e., increasing disturbances indicate higher vulnerability). The remaining three indicators, described in Table 3, represent the system state, i.e., constitute measures of ecological (position in fundamental niche space) and socioeconomic (silvicultural flexibility, cost intensity) adaptive capacity. Inherent adaptive capacity decreases (and consequently vulnerability increases) the closer a species (composition) is to its ecological limits, the lower the silvicultural flexibility and the higher the cost intensity of a management system are (assuming that more rigid and resource-demanding systems leave less potential for adaptive behavior). Four of the eight indicators were further decomposed into subindicators to cover different as-

**Table 2.** Vulnerability indicators for the sensitivity dimension (SE) of the vulnerability assessment framework. Indicator weights, as well as common indicator thresholds for recognition and tolerance, were derived in workshops with the AFF management planning team.

| | | | | | | Common thresholds | |
|---|---|---|---|---|---|---|---|
| Indicator | Weight | Subindicators | Description | Level | Methodology[a] | Recognition (±0.5) | Tolerance (±1.0) |
| Productivity | 0.290 | — | Gross stemwood productivity change (%) | Metric | PICUS | ±10% | ±15% |
| Timber stock | 0.226 | — | Change in average timber stock (%) | Metric | PICUS | ±5% | ±15% |
| Carbon stock | 0.081 | — | Change in mean ecosystem C stock (%) | Metric | PICUS | ±5% | ±10% |
| Biodiversity | 0.145 | Snags >10 cm dbh | Change in standing deadwood volume (categorical: <3 $m^3 \cdot ha^{-1}$; 3–16 $m^3 \cdot ha^{-1}$; >16 $m^3 \cdot ha^{-1}$) | Ordinal | PICUS | ±one class | ±two classes |
| | | Tree species diversity | Change in Shannon index based on tree species basal area shares (categorical:<0.3; 0.3–0.5; >0.5) | Ordinal | PICUS | ±one class | ±two classes |
| Disturbances | 0.258 | Bark beetles | Change in bark beetle damage relative to gross productivity (categorical:<5%; 5%–15%; >15%) | Ordinal | PICUS | ±one class | ±two classes |
| | | Storm | Change in predisposition rating (categorical: <0.33; 0.33–0.66; >0.66) | Ordinal | F&N(2001), PICUS | ±one class | ±two classes |
| | | Snow breakage | Change in predisposition rating (categorical: <0.33; 0.33–0.66; >0.66) | Ordinal | F&N(2001), PICUS | ±one class | ±two classes |

[a]PICUS, forest ecosystem model PICUS v1.41; F&N(2001), predisposition assessment system of Führer and Nopp (2001).

**Table 3.** Vulnerability indicators for the state dimension (ST) of the vulnerability assessment framework. Indicator weights and common categories were derived in workshops with the AFF management planning team.

| | | | | | | Common categories | | |
|---|---|---|---|---|---|---|---|---|
| Indicator | Weight | Subindicators | Description | Level | Methodology[a] | Low (0.0) | Medium (0.5) | High (1.0) |
| Fundamental niche | 0.425 | — | Ecophysiological stress scalar {0, …, 1} | Ordinal | S&L(1998), PICUS | <0.25 | 0.25–0.75 | >0.75 |
| Silvicultural flexibility | 0.362 | Adapted species composition | Share of basal area above stress threshold (see above) of 0.25 {0, …, 1} | Ordinal | S&L(1998), PICUS | <0.50 | 0.50–0.75 | >0.75 |
| | | Production goal | Stand development relative to the species-specific timber production goal {0, …, 1} | Ordinal | PICUS, AFF | <0.33 | 0.33–0.66 | >0.66 |
| Cost intensity | 0.213 | Silviculture costs | Costs of planting and tending (€·$ha^{-1}$) | Ordinal | PICUS, AFF | >4000 | 4000–2000 | <2000 |
| | | Management costs | Cost of harvesting interventions (€·$m^{-3}$) | Ordinal | PICUS, AFF | >27 | 27–22 | <22 |

[a]PICUS, forest ecosystem model PICUS v1.41; S&L(1998), niche model of Steiner and Lexer (1998); AFF, from databases and statistics of the Austrian Federal Forests.

pects and ensure an operational delineation of system boundaries (see Tables 2 and 3).

## Indicator valuation, standardization, and aggregation to vulnerability dimensions

Indicator values generated under the three climate change scenarios were evaluated with regard to the SFM objectives of the AFF. For the sensitivity (SE) indicators, two thresholds of common significance, a recognition threshold and a tolerance threshold, were defined together with the AFF. The recognition threshold characterizes a climate-driven indicator change (i.e., difference between indicator value under current climate and climate change) below which changes are negligible or not detectable for operational forestry; the tolerance threshold represents a change in indicator performance that was considered unacceptable by the AFF strategic management planning team, given the current AFF obligations to society. Applying these thresholds in conjunction with a preference function approach borrowing from multicriteria outranking methodology (Brans et al. 1986), the SE indicators were transferred to unit scale $\{-1, \ldots, +1\}$, where $-1$ and $+1$ indicate maximum negative and positive effects of climate change, respectively (i.e., a change greater than the tolerance threshold level). For instance, for indicator SE1, a change in timber productivity of 10% was set as recognition threshold, a 15% change as tolerance threshold. The linear preference function was used to evaluate cardinally scaled SE indicators, the level function for ordinally scaled SE indicators (see Brans et al. 1986). The ordinal ST indicator values were directly valuated at unit scale $\{0, \ldots, +1\}$ together with the AFF planning team (cf. step 5 in Table 1). For further details, we refer to Seidl et al. (2011) and Lexer and Seidl (2009).

Indicator aggregation by vulnerability dimension (i.e., sensitivity SE, state ST) was subsequently done via weighted summation. Compensation among indicators, however, was not accepted for disturbance intensity above the tolerance threshold (see Lexer and Seidl 2009; Seidl et al. 2011; step 6 in Table 1). Indicator weights, representing the importance of the individual indicators for the overall AFF management goals, were derived in a separate workshop with the AFF strategic management planning team (see Tables 2 and 3). This was accomplished by a two-phase ranking and scoring exercise in which team members first individually ranked indicators according to their importance and then assigned weights indicating relative differences between indicators on a scale from $\{0, \ldots, 100\}$, with mediated discussions after both steps to reach a consensus within the group. A sensitivity analysis addressing the effects of alternative indicator weights in the vulnerability assessment framework can be found in Lexer and Seidl (2009).

## Climate change vulnerability assessment

As a result of indicator valuation and aggregation, every simulated stand treatment program for a given combination of planning unit × stand type under a specific climate scenario was characterized by two "coordinates" (SE, ST), locating its position on the vulnerability surface (step 7 in Table 1). In general, negative sensitivity SE (i.e., a negative change in sensitivity indicators under climate change compared with baseline climate) in combination with a low value in state ST (i.e., low ecological and socioeconomic adaptive capacity) resulted in high vulnerability (cf. Luers 2005). To evaluate vulnerability, we retained the four vulnerability classes of Seidl et al. (2011), dividing the orthogonal vulnerability surface into areas of no (none or positive SE), low, medium, and high vulnerability (see also Lexer and Seidl 2009). The vulnerability assessment was conducted for a short- (2001–2020), mid- (2021–2050), and long-term (2051–2100) planning period.

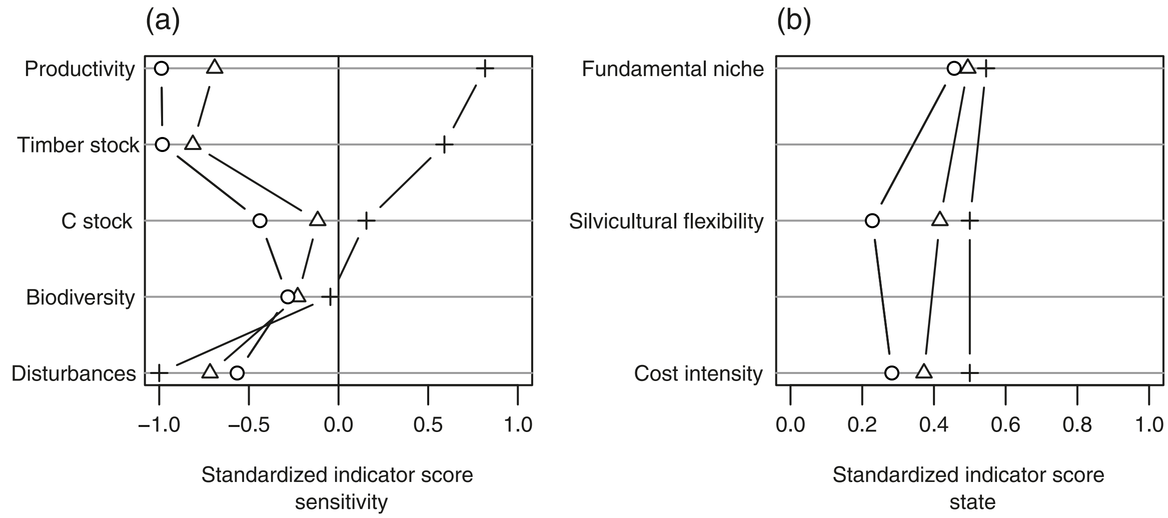
## Deriving adaptation measures based on vulnerability patterns

Considering future uncertainty and economic constraints, adaptation was devised under the general principle of Occam's razor, i.e., adapting current management as subtly as possible but as profoundly as necessary. As a prerequisite for this approach, i.e., to delineate and rank adaptation necessity, the performance of cSTP vulnerability indicators in the three study periods was analyzed in a cluster analysis to identify vulnerability patterns (step 8 in Table 1). We used divisive analysis to review the data structure and subsequently derived groups by means of partitioning around medoids (Kaufman and Rousseeuw 1990). Cluster silhouettes and intracluster dissimilarities were used to determine the optimal number of clusters (Kaufman and Rousseeuw 1990). Deriving general adaptation necessity and intensity from this clustering, we developed specific adaptation measures (aSTP) for every planning unit. We resorted to previous climate change impact assessments for the region (e.g., Lexer et al. 2002; Seidl et al. 2008), as well as to the general literature (e.g., Spiecker 2003), for an initial pool of potential adaptation options and explicitly took input from AFF management decision makers into account (step 9 in Table 1). Adapted stand treatment programs were subsequently simulated with PICUS under the different climate change scenarios, and their performances were evaluated in the vulnerability assessment framework (steps 10 and 11 in Table 1).

## Deducing adaptation recommendations

A final analysis step (step 12 in Table 1) was employed to extract adaptation recommendations from these detailed vulnerability assessment results. The rationale behind this step was to utilize the large number of explicitly studied planning units and their specific cSTP and aSTP, representing a wide variety in site and stand conditions, as well as silvicultural treatments, to deduce robust and more general recommendations (aSIG) of how to adapt the current AFF management guidelines (i.e., Weinfurter 2004). We used the data-mining approach Random Forests (RF) (Breiman 2001) to filter the detailed bottom-up information of cSTP and aSTP for robust strategic planning options and thresholds. RF was selected because of its non-parametric nature, superior accuracy, and probabilistic classification ability compared with ordinary classification trees. Furthermore, it allows for a coherent analysis of the importance of individual variables within the classification. The database for this analysis consisted of the assessment results (i.e., vulnerability scores) for the three climate change scenarios × three analysis periods × stand treatment programs (maximum of four) per planning unit. RFs were fitted to data stratified by the level of soil types ($n$ = 9). We used climate variables, species shares, and silvicul-

**Fig. 2.** Indicator profiles for (*a*) the sensitivity dimension (standardized indicator values of ±0.5 and ±1.0 correspond to the recognition and tolerance thresholds, respectively, as defined by the AFF), and (*b*) the state dimension (standardized indicator values range from low (0.0) to high (1.0) adaptive capacity) of the vulnerability assessment framework. Symbols indicate different vulnerability clusters: ○, acute cluster; △, severe cluster; +, mixed-effects cluster. Average values over all planning units per cluster for the period 2051–2100 and the most detrimental climate change scenario are displayed (see Tables 2 and 3 for indicator description).






tural treatments (e.g., increased thinning intensity, decreased rotation age) as explanatory variables to analyze the response variable vulnerability class by means of RF. Goodness of fit was evaluated by means of the out-of-bag error estimate, as well as the misclassification rate (Breiman 2001). We applied these RF (*i*) to extract "climate-smart" (i.e., low vulnerability) threshold levels for the dominant species Norway spruce and (*ii*) to determine the relevance of mixed species and silvicultural measures in reducing vulnerability. Following the precautionary principle, these analysis steps were conducted for the most detrimental climate scenario and the period 2051–2100 (i.e., the period with the highest exposure to climate change). As threshold for climate-smart systems, a RF-predicted probability of less than 50% in vulnerability classes medium or high was set. The relevance of admixed species and silvicultural options was assessed by means of the Gini importance, which is an indicator of how large the overall discriminatory power of a variable is in the RF classification (Breiman 2001). In summary, rather than imposing adaptation recommendations top-down or only qualitatively summarizing information from simulations, we used data mining in combination with an extensive database of stand-level vulnerability assessment results — covering a wide variety of environmental conditions and management strategies — to derive bottom-up adaptation options for the AFF.

## Results

### Adapting stand treatment programs

AFF forests were found to be highly vulnerable to climate change under current stand treatment programs, and the temporal development of vulnerability showed a distinct increase in the second half of the 21st century. The area assessed as highly vulnerable increased from 0 ha in the planning period 2001–2020 to 67 434 ha (41.0% of the study area) in 2051–2100. Conversely, the area of no or only low vulnerability decreased from 68.6% to 27.3% over this period (for details on contributing indicators and spatial distribution, see Seidl et al. 2011). The development of adaptation options described in the remainder of this contribution was focused on the 129 069 ha of the study area that showed elevated vulnerability (i.e., fell into vulnerability classes medium or high) in at least one of the three assessment periods.

An analysis of these planning units at indicator level (step 8 in Table 1) showed a moderate structure in the data, with the first two principal components accounting for approximately two-thirds of the variability. Cluster analysis revealed three distinct vulnerability patterns among the planning units (cluster silhouettes were 0.32, 0.20, and 0.60). (*i*) The first group of planning units showed strongly negative indicator performance and high vulnerability already in the first half of the study period (acute cluster). Planning units in this cluster were characterized by strong productivity losses and decreasing timber stocks alongside increasing levels of disturbances. Vulnerability was furthermore amplified by low silvicultural flexibility and high cost intensity, indicating a reduced potential to cope with adverse climate impacts (see Fig. 2). (*ii*) A second group (severe cluster) showed almost the same negative indicator performance as the acute cluster in the second half of the 21st century. It mainly differed with regard to the temporal progression, experiencing a more gradual increase in vulnerability over the study period. (*iii*) The third cluster (mixed effects) summarized planning units with mixed responses to climate change. Entities in this cluster were predominantly higher elevation mountain forests experiencing an increase in productivity, as well as timber and C stocks, in response to warming. However, at the same time, disturbances, particularly by bark beetle, were predicted to increase drastically from the low background levels under baseline climate (Fig. 2).

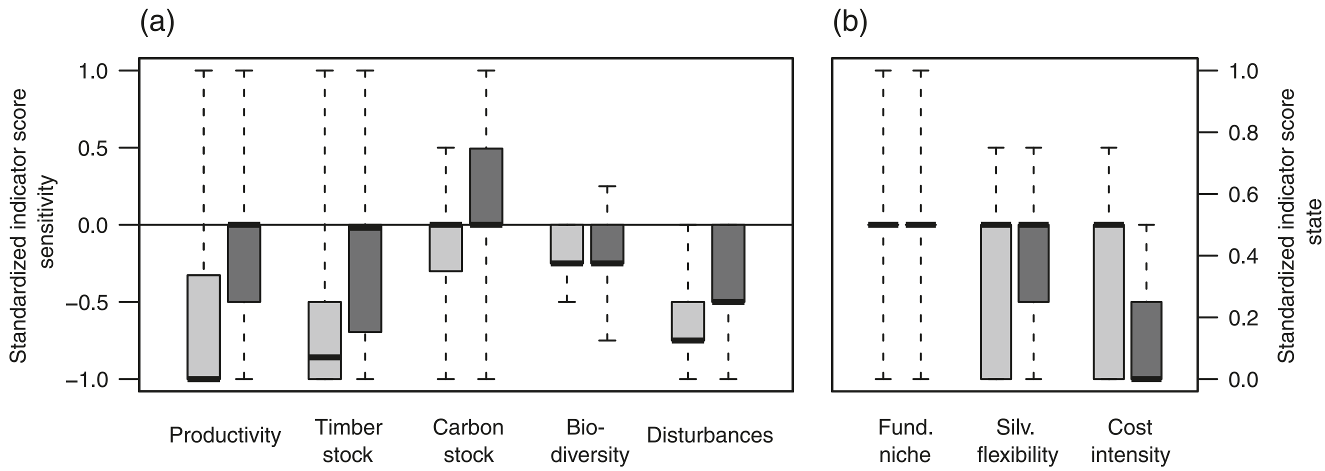
Adaptation measures were designed to address the vulnerability patterns of the particular clusters (aSTP, step 9 in Table 1). We developed planning unit specific aSTP along three general options for adaptation to climate change: (*i*) adapting

**Table 4.** Share of management target species composition (% area) under current (cSTP) and adaptation (aSTP) stand treatment programs in the three vulnerability clusters.

| | Cluster | | | | | |
|---|---|---|---|---|---|---|
| | Acute, 60 242 ha | | Severe, 59 025 ha | | Mixed effects, 9802 ha | |
| Forest type[a] | cSTP | aSTP | cSTP | aSTP | cSTP | aSTP |
| Pure Norway spruce | 5.4 | 0.0 | 20.8 | 0.0 | 74.8 | 74.8 |
| Norway spruce dominated | 69.8 | 0.0 | 30.0 | 5.7 | 25.2 | 1.1 |
| Mixed conifer | 0.0 | 0.0 | 0.0 | 20.3 | 0.0 | 24.1 |
| Mixed conifer broadleaf | 23.6 | 90.4 | 47.9 | 47.0 | 0.0 | 0.0 |
| Mixed broadleaf | 0.0 | 1.9 | 0.0 | 0.0 | 0.0 | 0.0 |
| Pure European beech | 0.0 | 0.0 | 1.3 | 1.5 | 0.0 | 0.0 |
| European beech dominated | 0.0 | 3.1 | 0.0 | 25.5 | 0.0 | 0.0 |
| Oak dominated | 1.2 | 4.6 | 0.0 | 0.0 | 0.0 | 0.0 |

[a]Pure, species share (basal area) >95%; dominated, 70% ≤ species share ≤ 95%; mixed, no single species >70%.

**Fig. 3.** Performance of the vulnerability indicators under current (light grey) and adapted (dark grey) stand treatment programs in the period 2051–2100 over all three studied climate change scenarios: (*a*) sensitivity dimension, (*b*) state dimension of the vulnerability assessment framework. Boxes denote interquartile range and median; whiskers indicate extreme values. Abbreviations: fund., fundamental; silv., silvicultural.



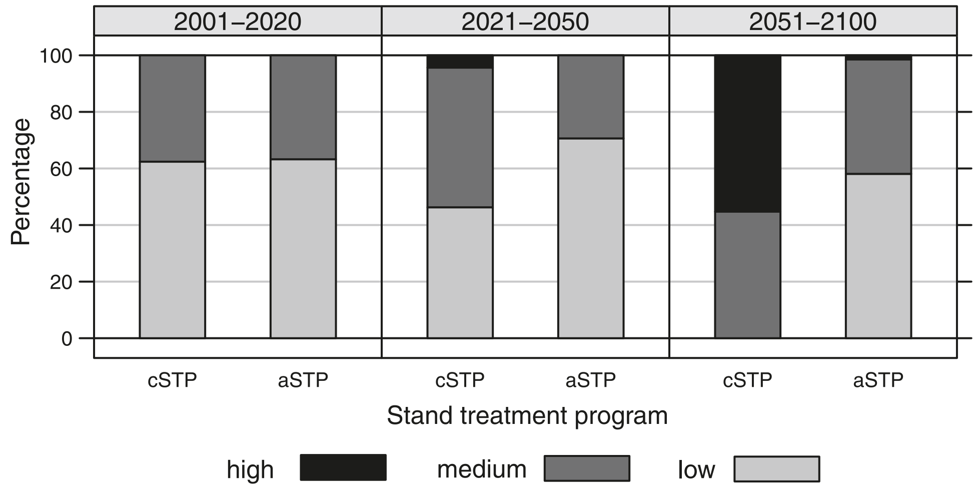



the target species composition, (*ii*) adapting silvicultural techniques, and (*iii*) adapting management intensity. For units in the acute cluster, a combination of all three options was employed towards a reduction of their immediate and considerable vulnerability. This implied a strong shift in target species composition from vulnerable Norway spruce dominated forest types to mixed forest types with a considerable share of broadleaved trees (Table 4). Furthermore, because of the fast emergence of vulnerability in this cluster, management intensities in the prevailing stands were increased (e.g., decreasing rotation periods) to accelerate the pace of adaptation. In addition, structural complexity and diversity of management interventions were increased by shifting towards a natural regeneration regime and a spatially clustered introduction of well-adapted species (e.g., gap openings with underplanting). For the severe cluster, which suffers comparable vulnerability in the second half of the 21st century, similar measures were implemented, however, at a slower pace, i.e., without reducing rotation periods of the prevailing stands. For planning units in the mixed-effect cluster, adaptation efforts focused on structural and intensity measures. Because the prevailing coniferous forests in this cluster were shown to respond predominantly positively to warming, adaptation options were aimed at utilizing this climate-mediated opportunity while reducing risks from disturbances. In response to the increasing productivity and the high risk in later stand development stages, rotation ages were adapted from 120 to 140 years (cSTP) to between 100 and 120 years in aSTP. Furthermore, thinning intensities were increased to counteract the buildup of high, disturbance-prone levels of timber stock. Lastly, spatially structured regeneration concepts adapted to mountainous environments (e.g., combined gap and strip cuts) were favored in aSTP of the mixed-effects cluster.

## Evaluating adaptation measures

As with cSTP, adaptation stand treatment programs (aSTP) were simulated and subsequently evaluated by means of the vulnerability assessment framework (steps 10 and 11 in Table 1). The results showed that an implementation of the proposed adaptation measures would be widely successful in counteracting the negative indicator performance under cSTP. With regard to the three most important sensitivity indicators in our analysis, adapted stand treatment programs significantly reduced losses in productivity, as well as standing stock, and mitigated the strong climate-induced increase in disturbances expected under cSTP (Fig. 3). State indicators representing adaptive capacity were generally less responsive to the adaptation measures suggested and even reflected a di-

**Fig. 4.** Temporal development of vulnerability categories under current (cSTP) and adapted (aSTP) stand treatment programs (percentages relative to planning units with elevated vulnerability under cSTP, representing 129 069 ha).




minishing economic potential for (additional) adaptive behavior as a result of the higher cost intensity of many aSTP compared with current management. However, even considering only the most detrimental climate change scenario per assessment unit, aSTP resulted in less than 1.5% of the study area being highly vulnerable in the period 2051–2100 compared with 55.2% under current stand treatment programs (percentages based on planning units with elevated vulnerability under cSTP). The highest efficiency of the adaptation measures in reducing vulnerability was found for the midterm planning period 2021–2050, where the effects of the gradually implemented adaptation measures already began to unfold while the exposure to climatic changes was still moderate (Fig. 4). Nonetheless, elevated residual vulnerability remained for 37 900 to 52 200 ha of the study area throughout the 21st century also under aSTP.

### Deriving adaptation recommendations from bottom-up stand treatment programs

Overall, the analysis at stand level yielded 1422 unique records of planning unit, climate condition (over all scenarios and time periods), stand type, silvicultural measures (cSTP and aSTP), and their corresponding vulnerability classification. This broad data set was used to derive robust adaptation recommendations for the studied AFF forests by means of data mining (step 12 in Table 1). RF was satisfactorily able to model this data set, with a mean out-of-bag error rate of 31.3% and a misclassification rate (none–low vs. medium–high vulnerability) of 12.8%.

Table 5 presents climate-smart thresholds for the main species Norway spruce, predicted with RF for the most detrimental climate change scenario in the period 2051–2100. Our analysis suggests that in colline planning units, Norway spruce will have to be replaced almost entirely by better adapted species to keep climate vulnerability low. It furthermore documents the relevance of local site conditions for management decisions with regard to tree species composition. Although shallow calcareous site types supported only very low shares of Norway spruce (e.g., site type 22) in the submontane elevation belt, the species was still found to be suitable on well-drained, fertile site types of the same elevation belt (e.g., site types 72 and 81). The RF-derived aSIG also acknowledged the generally positive climate response of Norway spruce on some high elevation planning units, resulting in a recommendation of high shares of the species to utilize positive climate effects such as increasing growth. However, on most planning units, some share of admixed species was found to be a primary adaptation option.

The set of possible admixed species in Norway spruce forests was ranked according to their importance within the RF classification, as expressed by the Gini index, i.e., we quantified which admixed species would have the greatest potential to reduce climate change vulnerabilities in Norway spruce forests (see Table 5). For our set of site and stand conditions, European beech and silver fir were found to be the most important species in reducing vulnerability in Norway spruce dominated stands. Furthermore, included in Table 5 are adapted silvicultural techniques and management intensities where they were of considerable discriminant importance in the RF, i.e., where they contributed significantly to reducing vulnerability. For mid- to high-elevation forests, retaining high shares of Norway spruce also under aSTP, increased thinning intensity, as well as reduced rotation age, were found to be beneficial silvicultural measures. Mixed deciduous forest types that were found to be well adapted in our vulnerability analysis are also included in Table 5; however, no quantitative analysis with regard to species shares was conducted due to the limited sample size.

## Discussion

### Methodology for deriving climate change adaptation recommendations

In this study, a coherent methodological concept to adapt operational forest management guidelines to climate change was presented. The cornerstones of our approach were (*i*) a strong foundation in scientific concepts (vulnerability assessment) and state of the art methodology (ecosystem modeling, MCDA, statistical analysis), (*ii*) a close involvement of decision makers as well as stakeholders, and (*iii*) a bottom-up assessment, acknowledging environmental heterogeneity and explicitly targeting the level of practical decision making.

**Table 5.** Adaptation recommendations for AFF commercial forests to maintain low climate change vulnerability throughout the 21st century. Values were derived by means of a Random Forests analysis of 1422 studied cases of unique climate and site conditions, species composition and silvicultural treatment, and their respective climate change vulnerabilities (see text for details).

| | | | Norway spruce forest types | | | |
|---|---|---|---|---|---|---|
| Elevation belt[a] | Ecoregion[a] | Site type[b] | Pa share (%) | Admixed species | Mixed deciduous forest types | Silvicultural measures |
| Colline | 5 | 86 | <5 | — | Fs–Ld/Ps/Qs, Qs–Cb | — |
| | 5 | 88 | <10 | — | Fs–Ld/Ps/Qs | — |
| Submontane | 1 | 81 | <80* | Fs, (Ld) | — | — |
| | 4 | 22 | <15 | Fs, Ps<20%, Qs | Fs, Qs–Cb | — |
| | 4 | 32 | <50 | Fs, Aa, Ap | Qs–Cb, Fs–obl | Prioritize conversion |
| | 5 | 22 | <5 | — | Qs–Cb, Fs–Ps/Qs | Prioritize conversion |
| | 7 | 72 | <60* | Fs, Aa, Ap | — | — |
| | 7 | 81 | <50 | Aa, Fs | — | — |
| Lower montane | 4 | 22 | <45 | Fs, Ld | Fs–Aa–obl | RP<120 years |
| | 4 | 23 | <65 | Fs, Aa | Fs–Aa/Ld/obl | — |
| | 4 | 32 | <50 | Fs, Aa, Ld, Ap | Fs–obl | RP<120 years |
| | 4 | 88 | <80* | Ld, Fs, Aa | Fs | — |
| Midmontane | 1 | 72 | >70 | Ld, Aa | — | RP<120 years, TH+ |
| | 1 | 81 | >75 | Ld, Aa | — | RP<120 years, TH+ |
| | 2 | 22 | <60 | Fs, Ld | — | RP<120 years |
| | 2 | 23 | <70 | Fs, Aa | — | — |
| | 2 | 32 | <65 | Fs, Aa, Ld | — | — |
| | 2 | 72 | >70 | Ld, Aa | — | RP<120 years, TH+ |
| | 4 | 22 | <55 | Fs, Ld | Fs–Aa–obl, Fs | RP<120 years |
| | 4 | 23 | <60 | Fs, Ld | ((Pa<45%)+Aa+Ld) <80% | RP<120 years |
| | 4 | 32 | <70 | Fs, Aa, Ld | — | — |
| | 4 | 41 | <70 | Fs, Aa, Ld | — | — |
| | 5 | 72 | <70* | Ld, Aa, Ap | — | RP<120 years |
| | 5 | 81 | <70* | Ld, Aa, Ap | — | — |
| | 6 | 22 | <40* | Fs, Ld | Fs–Aa–obl | RP<120 years |
| | 6 | 23 | <50 | (Pa+Ld)<75%, Fs | Fs–Ld | RP<120 years |
| | 6 | 32 | <65 | Fs, Aa, Ld | — | — |
| Upper montane | 2 | 23 | <90 | Aa, Ld | — | RP<120 years, TH+ |
| | 4 | 23 | <80 | Fs, Aa, Ld | — | RP<120 years |
| | 4 | 58 | <70* | Fs, Aa | — | — |
| | 6 | 23 | <65 | Fs, Aa, Ld | — | RP<120 years |
| Lower subalpine | 5 | 72 | >75 | Ld | — | RP<120 years, TH+ |

**Note:** Pa, Norway spruce; Aa, silver fir; Ld, European larch; Ps, Scots pine; Fs, European beech; Qs, oak species; Cb, hornbeam; obl, other broadleaved species; RP, rotation period; TH+, increasing thinning intensity. Species shares are relative to stand basal area; order of admixed species are according to their potential to reduce vulnerability (determined by their importance (Gini index) in the Random Forests classification). Pa share followed by an asterisk (*) indicates that thresholds were derived from auxiliary analysis due to ambiguous results of the Random Forests prediction.

[a]According to Kilian et al. (1994).
[b]According to Weinfurter (2004).



The deployed framework is in general agreement with theoretical adaptation considerations by, e.g., Maciver and Wheaton (2005) and Millar et al. (2007) and demonstrates an operational implementation of such concepts in the context of a federal forest agency. In this regard, it has to be noted that the aSTP of this study, albeit encompassing a wide variety of potential adaptation options from tree species selection to changes in silvicultural technique and management intensity, does not represent an exhaustive set of potential options for climate change adaptation in forest management. Aspects neglected in this study but with potential relevance for practical adaptation in forestry include, for instance, the explicit consideration of tree species provenances, epigenetic adaptation, and the introduction of alien tree species (e.g., McKenney et al. 2009).

A particular focus of this study was on the science–practice interface, i.e., working towards a science-based approach of devising intelligible and communicable management guidelines for adaptation. In this regard, we demonstrated that statistical methods such as cluster analysis and data mining can be employed to condense a large number of options explicitly studied with ecosystem models and MCDA to a set of comprehensible and communicable guidelines, while acknowledging the complex underlying interactions characteristic of social–ecological systems. A particular strength of this approach lies in the "depth" of analysis granted by the multilevel design, i.e., the higher level adaptation recommendations are explicitly grounded in stand-level analyses (specified down to the level of individual tree harvesting), and thus provide the information needed to communicate and implement the strategy in practical stand-level decision making. However, it has to be noted that while recognizing climate–site–vegetation–management interactions in our simulations, the local and regional landscape context was neglected in the current approach. In a practical implementation at the management unit level, the presented adaptation options should thus be seen as a portfolio of climate-smart measures to be employed in accordance with the local landscape context (cf. Crow and Gustafson 1997).

Furthermore, the adaptation measures proposed in this study are by no means the endpoint of the management planning process under climate change, but constitute only a step towards "climate-smart" forests. While adaptive components of management have been implemented in the simulation of stand treatment programs, strategic aspects have remained static throughout the assessment. Future adaptive cycles (see broken feedback arrows in Fig. 1) are important to further refine SFM under climate change, i.e., learn from specific experiences in the implementation of adaptation measures, incorporate new knowledge, and adapt to the actual socioeconomic and climatic changes as they unfold. Although future climate uncertainties were to some degree accounted for by means of a scenario analysis, social uncertainties, e.g., reflected in changing indicator preferences, have been neglected in the current analysis. In this regard, it has to be noted that the current indicator weights, favoring aspects of timber production over, for instance, C storage and biodiversity, exert a strong influence on the overall assessment results and recommendations (for the effect of different preference weights on the vulnerability assessment, see the sensitivity analysis of Lexer and Seidl (2009)).



### Practical challenges in adapting to climate change

The current study gives a strong indication that climate change adaptation will be necessary in Austrian forests to sustain forest functions and services at desired levels in the coming decades. It furthermore suggests that a distinct alteration of current forest landscapes might be necessary in many places to cope with climate change. Adopting a major change in tree species composition, suggested as necessary by our results to maintain low vulnerability, would distinctly alter the economic and technical business as usual of Norway spruce focused forest management of the AFF. At a larger scale, it would entail profound long-term changes for the Central European forest wood chain, which is currently strongly reliant on conifer sawlogs and fiber.

In terms of ecological consequences, it has to be noted that in this study, we deliberately employed native tree species in the development of aSTP. In a large number of cases, the proposed stand conversions would foster the role of native species that have been suppressed directly by management practices or indirectly by other interests (e.g., wildlife management) over the last centuries in favor of Norway spruce (i.e., silver fir, European beech; cf. Spiecker et al. 2004). Nonetheless, a simple orientation on the current natural vegetation composition, as sometimes advocated as a guideline for practitioners (e.g., Leitgeb and Englisch 2006), will also fall short of achieving climate-smart forests in many regions (cf. also Seidl et al. 2009*b*). Particularly at low-elevation planning units and medium to poorly drained sites, novel forest types beyond the current natural vegetation composition will be required to cope with future climate according to our findings (compare Table 5 with Kilian et al. 1994).

Another important issue is the potential cost of such profound management changes. Although we included an indicator of management costs in our study to account for a generally decreasing adaptive capacity with decreasing economic success, a detailed economic analysis of operational adaptation to climate change is still widely missing (but see, for instance, the recent work of Yousefpour et al. 2010). This is of particular importance as the practical implementation of such options will depend to a large degree on their economic consequences. In this regard, the positive economic effects of reduced rotation age and increased management intensity in areas where productivity is increasing (e.g., mid- to high-elevation sites) could help to offset added costs of necessary changes in tree species composition. However, as lowering rotation age could have detrimental effects on biodiversity and C storage (e.g., Noss 2001; Harmon and Marks 2002) beyond what is captured in the current indicator framework, trade-offs will have to be thoroughly scrutinized and monitored if such measures are adopted (Seidl et al. 2007*a*).

These complexities highlight the crucial role of field managers and decision makers for SFM under climate change. We conducted a series of field workshops with AFF practitioners in different forest types across Austria in the spring and summer of 2009 to disseminate the study results presented here, obtain feedback from field personnel regarding their practical implementation, and discuss potential limitations of the current study. From a knowledge–management perspective, a particular value of such a study lies in its potential as a science–practice interface, as good decision making depends first and foremost on people rather than models or theoretical frameworks (see Wolfslehner and Seidl 2010).

## Conclusion

Adapting to climatic changes will be necessary in large parts of the world's managed forests to sustain forest goods and services to society also under a drastically changed climate. The current study described the development of adaptation options for SFM in the Eastern Alps in Central Europe, integrating scientific concepts and close cooperation with practitioners, management planners, and stakeholders. Evaluating proposed adaptation measures showed that climate change adaptation based on native tree species and adjusted silvicultural techniques is capable of considerably reducing vulnerability. Furthermore, our findings highlight the bidirectional nature of adaptation, i.e., the need to address both climate-induced vulnerability and opportunities in adapting management practices, the importance of a timely implementation of adaptation, as considerable lead times are associated with silvicultural adaptation measures, and the in-parts drastic changes in forest landscapes and their management that might be necessary to avoid large-scale adverse climate impacts on forest goods and services. The fact that residual vulnerability remained considerable even under some of the adapted treatment programs presented here underlines the importance of incorporating climate change adaptation into a continuous adaptive management planning process. Overall, we remain confident that, given a foresighted stewardship, forest ecosystems in the Eastern Alps will be able to provide vital functions and services to society also under a changing climate.

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