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Trade-offs in ecosystem services

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Thomas Cordonnier, Valentine Lafond, Manfred J. Lexer, Zhun Mao and Florian Irauschek

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Abstract:

We provide a brief overview of some approaches developed and results obtained in ARANGE to study the effect of climate change on ecosystem services (ES) as well as trade-offs and synergies between ES, based on business-as-usual management (BAUM) scenarios. This overview if followed by a short synthesis and two manuscripts: (1) one addressing the effect of climate change on the provision of ES at the stand scale for BAUM scenarios in five case study areas (Mao et al. in preparation); (2) the other addressing the effect of climate change on ES at the landscape scale for the Austrian case study area (Irauscheck et al. in revision for Reg Environ Change). A special issue in Reg Environ Change will provide complementary results for other case study areas.

TABLE OF CONTENTS

1 Introduction

In forestry, the effect of management practices and climate change on the provision of ecosystem services (ES) represents a central issue. This question is further complicated by direct and indirect interactions between ES (for instance supporting ES with provisioning ES), which generally lead to trade-offs or synergies depending on the indicators and the forest systems considered. For instance, timber production and biodiversity conservation are responsible for one of the most acknowledged and problematic tradeoffs related to forest management (Lafond et al. in press) while biodiversity conservation and protection against rock falls can sometimes work in synergy (Fuhr et al. 2015).

Usually, the analyses of ES and their sensitivity to climate change or management are performed through modelling approaches. However, empirical approaches based on landscape inventories have also been used. Forest dynamics models permit the integration of several processes (climate change, stand demography, management actions) and allow assessing their effect on ES provisioning in the long term (more than a century). For instance, Schwenk et al. (2012) studied the effect of four different management systems on carbon storage, wood production and bird diversity conservation using the Forest Vegetation Simulator applied to northern hardwood-conifer forests in Vermont (USA). Using an optimization procedure, they found that the clearcut and the individual tree selection systems performed better than the shelterwood system. In the same vein, Duncker et al. (2012) used the forest growth simulator W+ and multivariate analyses to study the effect of five management scenarios (from a very intensive scenario to a no-management scenario) on several ES in spruce and beech forests in Germany, revealing complex relationships but a clear trade-off between biodiversity conservation and wood production.

The main limit of these two examples is to consider highly contrasted management scenarios with, in the end, a difficulty to disentangle the underlying management actions that shape the trade-offs or synergies between ES. Another difficulty lies in the effect of climate change, which in relation to ES trade-offs has been addressed only very recently (see for instance Ray et al. in press, Temperli et al. 2012 and Elkin et al. 2013). Finally, we lack established approaches providing a comprehensive way of analyzing the effect of management on ES at different scales, from local stands to landscapes.

In this report, we provide a brief overview of some approaches developed in the ARANGE project to study ES for the business-as-usual management (BAUM) scenarios in several case study areas. ARANGE aimed at assessing the effect of management and climate change on four ES (wood production, carbon storage, biodiversity conservation and protection against gravitational hazards) in seven different case study areas in Europe. Details about the seven case-study areas, the models, the climate change scenarios, the management scenarios and the ES indicators used in the project are available in ARANGE Deliverables D1.3, D1.4, D2.1, and D2.2. Three approaches are presented in this overview (the first two being detailed in related manuscripts in the Appendix):

(1) the first one addresses the effect of climate change on BAUM at the stand scale for five case study areas (Mao et al. in preparation);

(2) the second one addresses the effect of climate change on ES at the landscape scale for the Austrian case study area (Irauscheck et al. in revision for Regional Environmental Change);

(3) a third one presents a novel approach to study trade-offs and synergies between ES, based on Pareto fronts (Lafond et al. 2015).

A special issue in *Regional Environmental Change* provides complementary results for other case study areas (Bugmann et al. in preparation). Another special issue in an international scientific journal based on the results presented in the international scientific conference “Mountain Forest management in a Changing World” in Smokovce, Slovakia (6-9 July 2015) organized by the ARANGE consortium will also provide some insights, especially concerning the effect of alternative management scenarios compared to BAUM.

2 Effect of climate change on the provision of ES at the stand scale

Based on Mao et al. (in preparation). For details see Appendix.

A cross case study analysis was carried out on BAUM simulations (planning period 100 years) for five different case study areas (Spain, France, Austria, Bulgaria and Slovakia). Using the baseline climate scenario as a reference, a standardized indicator of vulnerability of ES was defined to compare the effect of climate change on the representative stands in the different case study areas (% of variation compared to baseline climate scenario). A subset of ES indicators was selected to avoid redundancy (for instance the dead wood volume was highly correlated to the number of snags). Then, for each representative stand, an ES indicator was judged vulnerable if its value was reduced by at least 10% compared to the reference value under the baseline climate scenario. When not vulnerable (> -10%), the impact of climate change on the provision of the ES could be either neutral (vulnerability between -10 and +10%) or positive (≥ + 10%). Logistic regression was used to analyze the effect of a small set of interpretable independent variables (initial temperature, initial precipitation, initial basal area, initial percentage of broadleaves, climatic changes over the 100 years study period ΔT, ΔP) on ES vulnerability. In order to test whether results were consistent across different stand types, three different set of representative stands were analyzed: even-aged stands, mixed stands (that involve both even-aged and uneven-aged stands) and all stands grouped together.

The proportion of representative stands with vulnerable ES increased through time and with increasing severity of climate change. Although less pronounced, we also observed for all ES an increase in the proportion of representative stands with positive effect of climate change. Under the most extreme climate change scenario, all ES are projected to either increase or decrease in the French, Austrian and Bulgarian case study areas by 2081-2100 (Figure 1). In contrast, shifts in ES levels are projected to be moderate in the Slovakian and Slovenian case study areas, and slight in Spain. However, within each case study area, the impact of climate change (either positive or negative) on representative stands differs between ES.

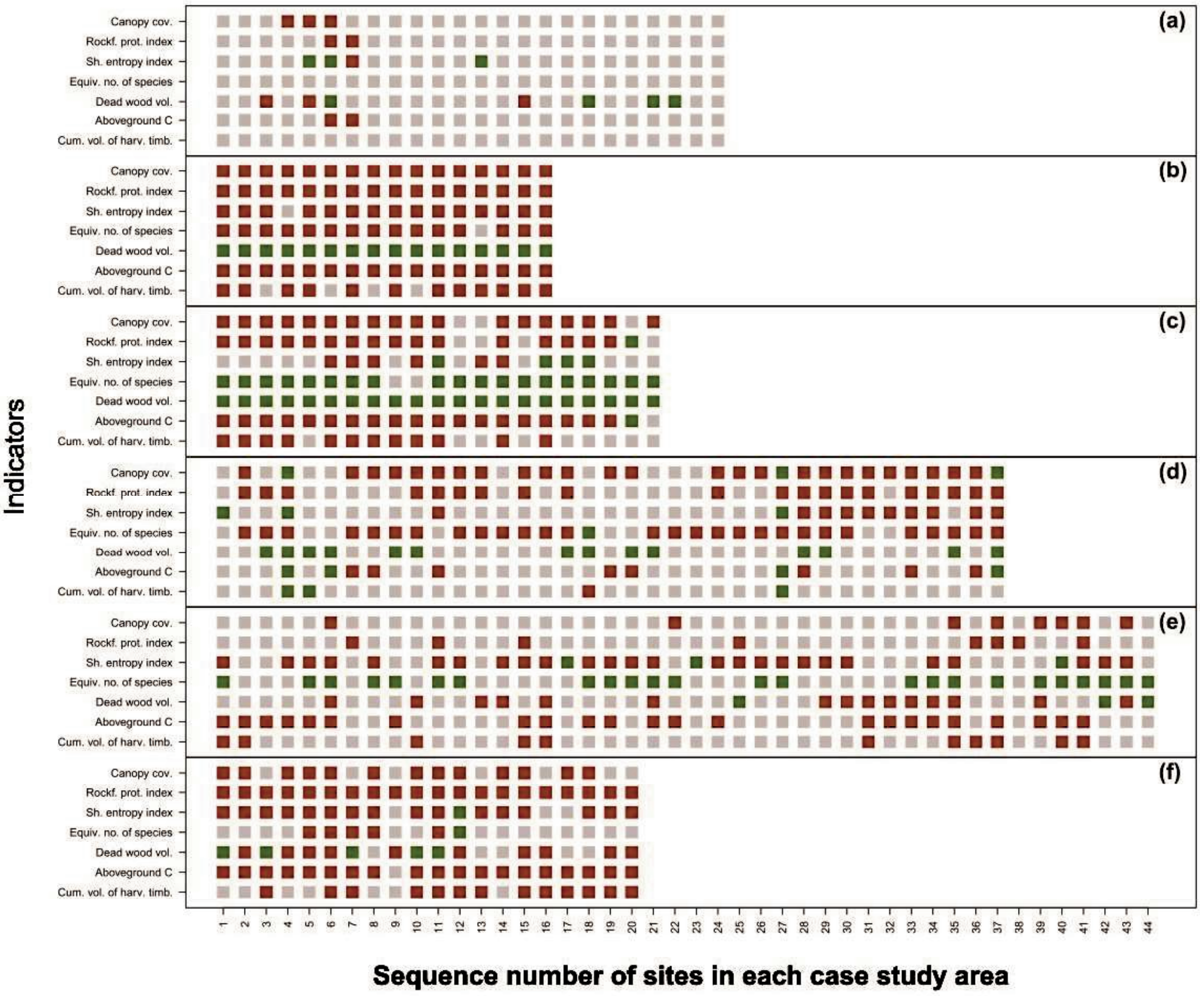

Figure 2. Distribution of status types of services in each of the case study areas (a: Spain, b: France, c: Austria, d: Slovenia, e: Slovaquia, f: Bulgaria). This figure is generated based on the most extreme climate change scenario and the period 2081 to 2100. The three colours respresent the three status of ecosystem services: green – gain, grey – maintaining, red –loss.

Usually, vulnerability of ES increased with the severity of climate change (high increase in temperature combined with a decrease in precipitation), except for two indicators of biodiversity conservation: the dead wood volume and the tree species diversity. Initial forest conditions, such as basal area, had no significant effect on the vulnerability of ES, except a slight beneficial effect on cumulative volume of harvested timber. The percentage of broadleaves had comprehensive effects on biodiversity conservation: it slightly favored dead wood volume, but lead to a decline of tree species diversity and tree size diversity.

In conclusion, in this study, the impact of climate change is usually negative for wood production, carbon storage and protection and positive or negative on biodiversity conservation depending on the initial conditions (e.g. the percentage of conifers) and the indicator considered. A Principal Component Analysis was performed to detect correlations between vulnerability of ES indicators (Figure 2). This analysis showed trade-offs between some biodiversity conservation indicators (tree species diversity and dead-wood volume) and all other indicators.

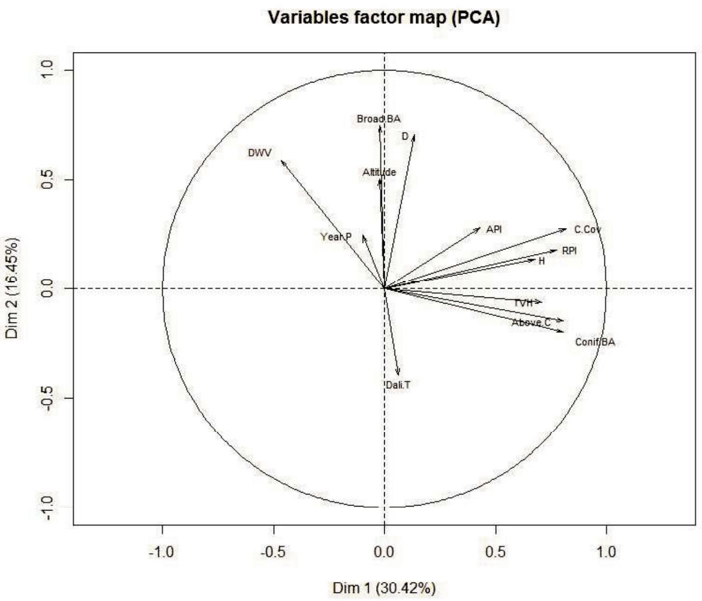

Figure 2. Principal Component Analysis of the vulnerability values of ES indicators performed with data of BAUM and climate change scenarios in five case study areas for the period 2081-2100. Two groups are distinct: ConiferBA (basal area of conifers) driven and BroadBA (basal area of broadleaves) driven. The BroadBA driven group appears to be mostly related to climatic factors (Daily Temperature, Yearly precipitation, and Altitude) while the ConiferBA group is related to the vulnerability of most ES (except the equivalent number of tree species and the dead wood volume), especially the vulnerability of the above ground carbon and the total timber volume harvested.

3 Effect of climate change and management on the provision of ES at the landscape scale

Based on Irauscheck et al. (in revision for Regional Environmental Change). For details see Appendix.

The combined effect of climate change and management scenarios (here BAUM and no management; NOM)) on ES provisioning at the landscape scale has been studied in a catchment of 250ha in the Austrian case study area (Irauschek et al. in revision). The spatial pattern of ES provisioning and multi-functionality and the way the spatial scale of ES assessment affects multi-functionality were investigated using the PICUS forest dynamics model combined with a specific landscape approach developed by Maroschek et al. (2014). In this forest area, the main management scenario consists in variable patch cuts along skyline tracks (maximum patch width of 50m and a mean length of 40-50m). The main originality of this study lies in the variation of the cell size used to calculate mean ES provisioning. Such a variation allowed the authors to analyze the sensitivity of ES provisioning and multifunctionality assessment depending on the spatial grain size (Figure 3). This last analysis was performed for non-timber ES: carbon storage, bird habitat provision and protection against avalanches and landslides. The timber drain from the catchment was considered at landscape level.

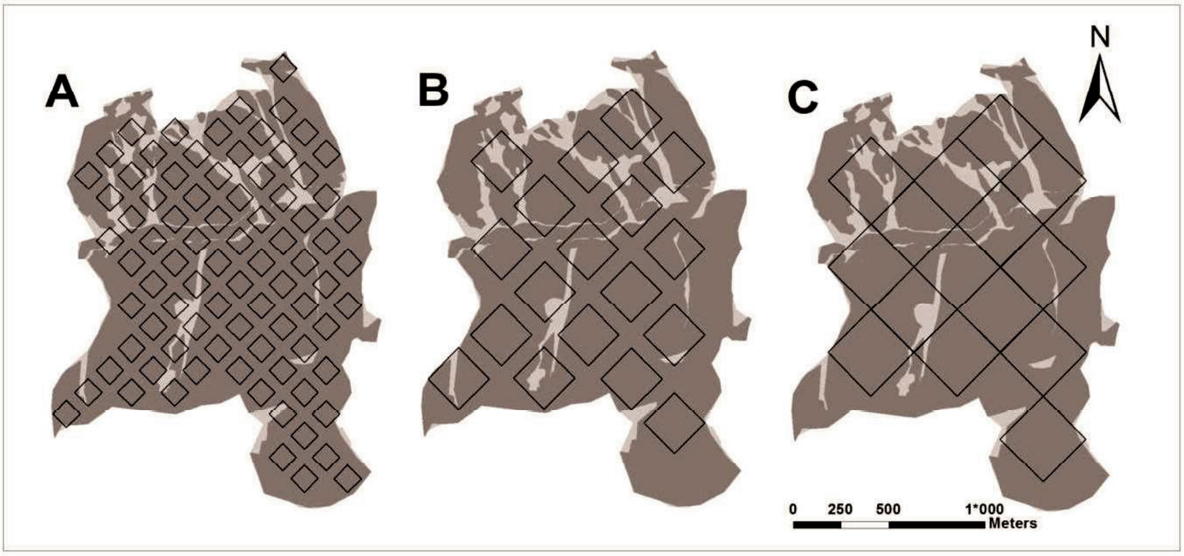

Figure 3. Three grain sizes for the assessment of ES indicators in the study landscape Montafon in Austria (indicated as black boxes for A: 1ha, n=84; B: 5ha, n=18; C: 10ha, n=15). Dark grey area shows forested area, light grey non-forest area.

For BAUM, a significant decrease in standing stocks and total volume harvested was observed only for climate change scenarios showing a significant decrease in precipitation. For all climate change scenarios, the carbon storage, the share of Silver fir and admixed broadleaves species decreased while tree size diversity increased (in this case due to young age classes initiated by regeneration fellings). Climate change tended to favor other biodiversity indicators (density of snags and bird habitat quality). The NOM showed a similar pattern but with differences in the magnitude of spatial variations. For instance, the variation was stronger for size diversity and volume stocking. The protection efficiency against landslides and avalanches, high in the two scenarios (BAUM, NOM), was almost insensitive to climate change.

Concerning complementarity between ES, the multifunctional area (i.e. the percentage of area with good provision of all ES) decreased with the number of ES considered. The largest spatial variation for ES was obtained for the smallest cell size (1ha) and the multifunctional area increased in general with cell size due to better complementarity between non-timber ES at coarser grain in the landscape. The multifunctional area was also sensitive to the climate change scenario: it increased for moderate warming but decreased for the most extreme climate change scenario (Figure 4). The no management scenario had in general higher multifunctional area shares but at the cost of no harvested timber.

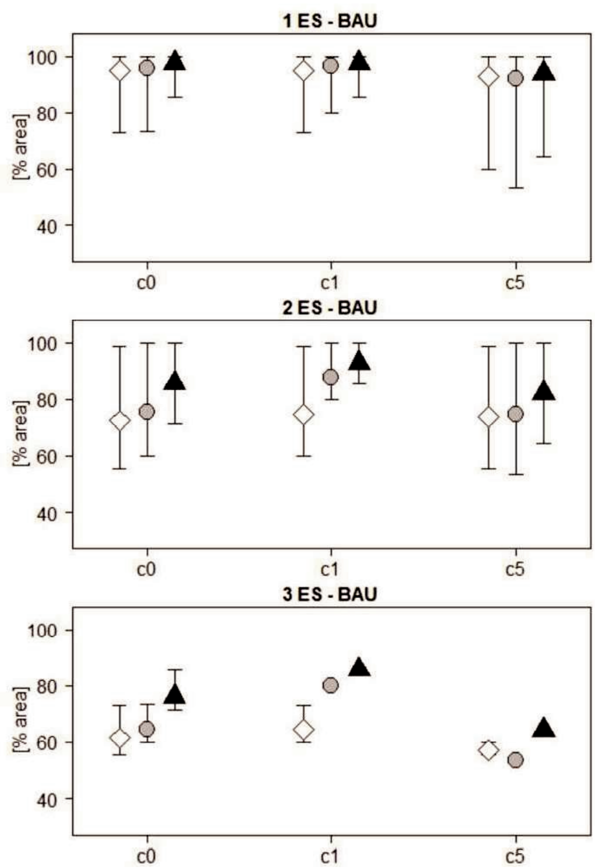

Figure 4. Multifunctional share of landscape area (bundles of ES in performance category 2 (moderately good) or 3 (good) in period P3 (2078-2110)) under current climate (c0) and two climate change scenarios (c1, c5) under BAU management. Assessment scale: 1ha (white diamond), 5ha (grey circle) and 10ha (black triangle) samples. Symbols represent mean area percentage, whiskers indicate worst and best case within given situation. Considered ES: Carbon storage, bird habitat, protection against avalanches and landslides

4 Exploration of synergies and trade-offs between ES using metamodels and Pareto fronts

Some new approaches were developed in the ARANGE project to specifically explore trade-offs and synergy patterns between ES in mountain forests (see also Irauschek et al. (in revision) above). For example, Lafond et al. (in press) used a two-step sensitivity analysis applied to demographic and management parameters of Samsara2 (Courbaud et al. 2015) to build metamodels for different indicators related to production, biodiversity conservation and protection in uneven-aged stands. These metamodels were then used to explore the factorial space (varying management parameters) and to search for Pareto fronts in the multi-criteria space (ES indicators). This approach allowed the detection of efficient management scenarios, which locally maximized all criteria (scenarios along the Pareto front) and revealed synergies or trade-offs between indicators of different ES (Lafond et al. 2015). A comparison between BAUM, alternative managements and the optimum scenarios can then be conducted to assess the distance to the front (and thus to optimality), describe the main differences between scenarios and indicate the ways to improve the provision of several ES at the same time. Spatial scale of this analysis was the stand level.

Although only based on three ES, the first results of the application of the Pareto fronts approach highlighted interesting patterns (Figure 5). First, a strong trade-off between timber production and biodiversity (deadwood volume) was observed, as one indicator could not be increased without involving a decrease of the other indicator (considering only optimal management scenarios of the Pareto front). Second, the relation between timber production and protection against rockfalls appeared to be more complex, with a synergy for low values of both indicators, an optimum reached for intermediate values, and a trade-off pattern when trying to maximize biodiversity. This pattern needs however to be confirmed by repeating the analysis for different initial stand states and tree demography. Third, no clear pattern was observed between timber production and protection. But this should also be confirmed by extended analysis.

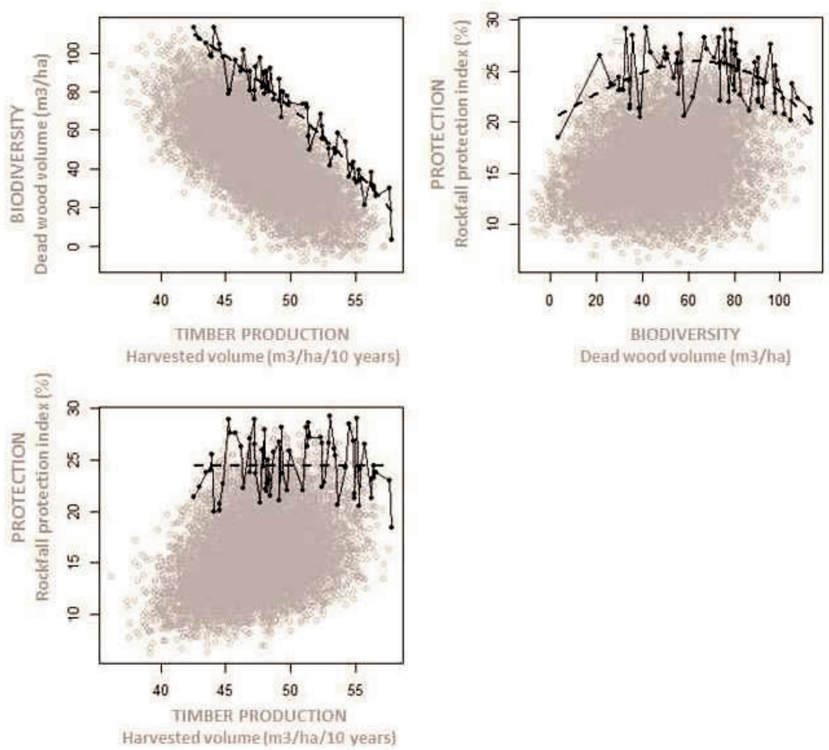

Figure 5. Illustration of the Pareto front approach for three indicators of ES: timber production (harvested volume), biodiversity (deadwood volume) and protection (Rockfall protection index). These Pareto fronts were obtained using metamodels derived from Samsara2. Grey dots represent predictions of the three meta-models for a set of combinations of uneven-aged management parameters. Black dots figure the non-dominated scenarios defining the Pareto front and a regression on these points (dotted line) characterize the observed pattern (trade-off, synergy or no pattern). From Lafond et al. (2015).

Analyzing in detail the Pareto front between timber production and deadwood volume (Figure 6), Lafond et al. (2015) also noticed that most scenarios of the Pareto fronts were characterized by high harvesting diameter, low proportion of mature trees harvested as well as very low or no thinning operations. The differences between scenarios located on the front were mainly related to a gradient of deadwood retention. The comparison of BAUM and AM scenarios (in the Vercors case study area, France) to the front highlighted that neither of them were located on the front. BAUM scenarios were even far from the optimal management scenarios and alternative management scenarios (AM) aiming at the increase of biodiversity while maintaining timber production (AM4 and AM5, triangles and diamonds in Figure 3) did not converge toward the front (Figure 6).

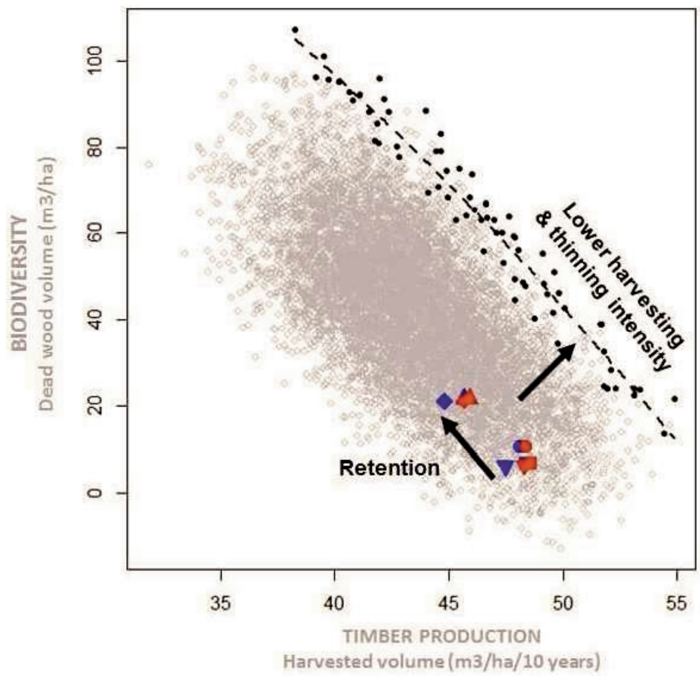

Figure 6. Analysis of the trade-off between a timber production indicator (harvested volume) and a biodiversity indicator (deadwood volume) based on Pareto fronts obtained using metamodels derived from Samsara2 for three ES indicators (third dimension is protection against rockfalls; not shown). Grey dots represent predictions of the two meta-models for a set of combinations of uneven-aged management parameters. Black dots figure the non-dominated scenarios defining the Pareto front and a regression on these points (dotted line) characterize the observed pattern (here a trade-off). Colored figures represent business as usual (squares) and alternative management scenarios for two representative stands (RST1 in blue, RST2 in red) of the Vercors case study in the ARANGE project (top-down triangle for AM2= low harvesting diameter; circles for AM3= gap; triangles for AM4= retention measures; diamonds for AM5 = combination of AM2 and AM4). Text and arrows synthesize the main trends resulting from the detailed analysis of the highlighted management scenarios (combination of uneven-aged management parameters). From Lafond et al. (2015).

5 Synthesis

5.1 Impact of climate change on the provision of ES

The first two studies presented in this report showed that the impact of climate change on ES depended on the indicator and on the climate change scenario considered. Globally, most studies of the ARANGE project (Irauschek et al., Mao et al.; but see also Langner et al. 2015, Mina et al. 2015) predicted a negative impact of climate change on carbon storage, timber production and protection against natural hazards, at least for the most extreme climatic scenarios. The impact on biodiversity depended on the indicator considered, with a negative impact on tree species diversity (Mao et al.) or on the share of fir and broadleaves (Irauschek et al.), but a positive impact on indicators related to the presence of dead trees (snags density and habitat quality in Irauschek et al., deadwood volume in Mao et al.), as they were indirectly favored by the increased tree mortality under climate change conditions. The impact of climate change (either positive or negative) depended on the climate scenarios considered and generally increased with its severity (Mao et al.). For example, Irauschek et al. observed a negative impact of climate change on timber production only for the most extreme scenario.

Some differences were however noticeable between sites and/or models. For example, Irauschek et al. did not observe any significant impact of climate change on protection, though Mina et al. (2015) did observe a negative impact when running simulations on the same site (Austrian case study area) but with a different model (ForClim instead of PICUS) and approach (stand scale instead of landscape scale). Moreover, the cross-site comparison conducted by Mao et al. interestingly highlighted strong differences in the response of ES to climate change among the different case study areas of the ARANGE project. The impact of climate change appeared to be strong in the French, Autrian and Bulgarian case study areas, whereas it was moderate or low for the three other sites (Spain, Slovakia, Slovenia).

5.2 Trade-offs and synergies between ES

By explicitly assessing multifunctionality and considering spatial patterns within a landscape, Irauschek et al. confirmed that simultaneous provision of several ES at the local scale is a hard task (especially when working at a very fine scale, e.g. 1ha patches). It is getting even harder when increasing the number of ES considered. Indeed, although Irauschek et al. observed a certain complementarity between non-timber ES (especially at large scale), all studies confirmed the existence of a strong trade-off between deadwood-related biodiversity indicators and other ES (Mao et al.), and especially timber production (Lafond et al. 2015). This trade-off is well known, due to the negative impact of forest management (compared to “no management scenarios”) on indicators related to large trees (Mina et al. 2015, Irauschek et al.).

However, Lafond et al. (2015) showed that specific management actions (extensive management and deadwood retention) can allow a compromise between deadwood volume and timber production at the stand scale. Moreover, the provision of multiple ES can also be reached at the landscape scale, thanks to a mosaic of “compromise” and “specific or dedicated” management scenarios (e.g. favoring either timber production or biodiversity conservation). “No management” scenarios should also be included in such a landscape mosaic, as they are favorable to numerous ES, especially (but not only) biodiversity conservation, with the exception of timber production (Irauscheck et al., Mina et al. 2015).

Although most studies conducted in ARANGE assessed trade-offs and synergies between ES follow a common approach and employed a common set of indicators, different techniques were mobilized to study the relation between indicators and to characterize trade-offs. Trade-offs between ES indicators can indeed be detected by negative correlations (opposed PCA directions, Mao et al.), high root mean square error (Langner et al. 2015), complementarity to assess multifunctionality (Irauscheck et al.) or by maximizing all indicators along Pareto fronts.

The Pareto front technique revealed as especially interesting to characterize trade-offs and synergy patterns thanks to a dense exploration of the factorial space, here allowed by the use of metamodels (for faster calculations). The identification of optimal management scenarios and their characterization was also interesting to assess and discuss management scenarios (BAUM and AM). Such an approach allows circumventing some limits of previous studies, as each management action is here considered as a continuous variable (continuous variation of all management parameters instead of predefined discrete parameter combinations) and its qualitative as well as quantitative effects can be assessed (control of initial state, tree demography). Moreover, the selection of interesting management scenarios is not influenced by pre-defined preferences or priorities among ES, as it is often the case with multicriteria analysis (Schwenk et al. 2012, Langner et al. 2015), but can be done a posteriori, based on the observed patterns, management preferences and scaling issues (i.e. stand scale compromise versus landscape “patchy” multifunctionality). This method is, however, computationally expensive and may require the use of metamodels (see Lafond et al. in press), with possible loss of information and precision. Such an approach is complementary to more classical multicriteria analyses that were also carried out in the ARANGE project (Deliverable D4.2). The detailed comparison of the different approaches used (and results obtained) will be conducted in the near future and will lead to a synthesis paper on the study of trade-offs and synergies between ES in the ARANGE project.

6 References (*affiliated to the ARANGE project)

*Bugmann et al. (in preparation). Impacts of business-as-usual management on ecosystem services in European mountain ranges under climate change: Introduction. *Regional Environmental Change*

*Courbaud B, Lafond V, Lagarrigues G et al. (2015) Applying ecological model evaludation: lessons learned with the forest dynamics model Samsara2. *Ecological Modelling* 314:1-14.

Da Silva D, Han L, Faivre R, Costes E (2014) Influence of the variation of geometrical and topological traits on light interception efficiency of apple trees: sensitivity analysis and metamodeling for ideotype definition. *Annals of Botany* 114:739–752

Duncker PS, Raulund-Rasmussen K, Gundersen P, Katzensteiner K et al. (2012) How forest management affects ecosystem services, including timber production and economic return: Synergies and trade-offs. Ecology and Society:17(4)

Elkin C, Guiterrez AG, Leuzinger S, Manusch C et al. (2013) A 2°C warmer world is not safe for ecosystem services in the European Alps. *Global Change Biology* 19:1827-1840

*Fuhr M, Bourrier F, Cordonnier T (2015) Protection against rockfall along a maturity gradient in mountain forests. Forest Ecology and Management 354:224-231

*Irauschek F, Rammer W, Lexer M (in revision). Can the current management regime maintain multifunctionality in an Alpine forest landscape under conditions of climate change. *Regional Environmental Change*.

*Lafond V, Cordonnier T, Courbaud B (in press) Reconciling biodiversity conservation and timber production in mixed uneven-aged mountain forests: Identification of ecological intensification pathways. *Environmental Management*

*Lafond V, Cordonnier T, Zhun M, Courbaud B (2015) Studying tradeoffs between timber production, protection and biodiversity in uneven-aged mountain forests. Conference Mountain Forest Management in a Changing World, 7-9 July 2015, Smokovce, Slovakia.

*Langner, A, Irauschek, F, Perez S, Pardos M et al. (2015) Value-based trade-offs between ecosystem services from European mountain forests. Conference Mountain Forest Management in a Changing World, 7-9 July 2015, Smokovce, Slovakia.

*Mao Z, Elkin C, Manfred L, Cordonnier T. (2015) Local impacts and regional patterns in mountain forest ecosystem service responses to climate change in Europe. Conference Mountain Forest Management in a Changing World, 7-9 July 2015, Smokovce, Slovakia.

Maroschek M, Rammer, W, Lexer MJ (in press) Using a novel assessment framework to evaluate protective functions and timber production in Austrian mountain forests under climate change. *Regional Environment Change*

*Mina M, Cailleret M, Bugmann H (2015) Is adaptive management needed to maintain ecosystem services in a range of European mountain forest stands? Conference Mountain Forest Management in a Changing World, 7-9 July 2015, Smokovce, Slovakia.

*Zhun M, Elkin C, Lexer MJ, Cordonnier T et al. (in preparation) Global impacts and regional patterns in mountain forest ecosystem service responses to climate change in Europe.

Perlman J, Hijmans RJ, Horwath WR (2014) A metamodeling approach to estimate global N2O emissions from agricultural soils. *Global Ecology and Biogeography* 23:912–924

Ray D, Bathgate S, Moseley D, Taylor P et al. (in press) Comparing the provision of ecosystem services in plantation forests under alternative climate change adaptation management options in Wales. *Regional Environmental Change*

Schwenk WS, Donovan TM, Keeton WS, Nunery JS (2012) Carbon storage, timber production, and biodiversity: comparing ecosystem services with multi-criteria decision analysis. *Ecological Applications* 22:1612–1627

Temperli C, Bugmann HKM, Elkin C (2012) Adaptive management for competing forest goods and services under climate change. *Ecological Applications* 22:2065-2077

APPENDIX

MANUSCRIPTS

Zhun M, Elkin C, Lexer MJ, Cordonnier T et al. (in preparation) Global impacts and regional patterns in mountain forest ecosystem service responses to climate change in Europe.

Irauschek F, Rammer W, Lexer M (in revision). Can the current management regime maintain multifunctionality in an Alpine forest landscape under conditions of climate change. *Regional Environmental Change*

DRAFT VERSION

Global impacts and regional patterns in mountain forest ecosystem service responses to climate change in Europe.

Zhun Mao[1,2,*], Ché Elkin[3,4], , Manfred J. Lexer[5], Thomas Cordonnier[1,2] and other ARANGE contributors

Affiliations

1 IRSTEA, UR EMGR, 2 Rue de la Papeterie, BP 76, 38402 Saint-Martin-d'Hères Cedex, France
2 Université Grenoble Alpes (UGA), 38402 Grenoble, France
3 Swiss Federal Institute of Technology, ETH Zurich, Department of Environmental Systems Science, Forest Ecology, Universitäatstrasse 22, Zürich CH-8092, Switzerland
5 Ecosystem Science & Management Program University of Northern British Columbia 3333 University Way Prince George, B.C. V2N 4Z9
6 University of Natural Resources and Life Sciences (BOKU), Gregor Mendel Straße 33, A-1180 Wien, Österreich

*Corresponding author

Abstract

In a context of climate change, the future of ecosystem services in European mountain forest remains uncertain. Global and regional patterns of the evolution of these services among a range of environmental conditions are especially lacking. Finding main differences as well as common responses accross Europe is of major importance to define relevant regional strategies for climate change adaptation. Using individual based forest dynamics models, we estimated and compared the evolution of four types of ecosystems services (timber production, carbon stock, biodiversity conservation and protection against natural hazards) of mountain forest stands under current management, in case study areas from six European countries (Spain, France, Austria, Slovenia, Slovakia and Bulgaria) for 100 years. The vulnerability of the ecosystem services was investigated under one baseline and five climate warming scenarios. Using multinomial regression analyses, the impact of climate change on ecosystem service followed rather similar trends in the different case studies areas. Yet, the impact could be significantly moderated by climatic conditions of each study site. Overall, this study suggests that the current forest management in Europe might not be safe enough for stable ecosystem services provision in the future.

Key words: ecosystem service, biodiversity, timber production, carbon storage, natural hazards, climate change, mountain forests, modelling.

1 INTRODUCTION

In Europe, 36% of the continent surface belongs to mountain ecosystem, nearly the half of which was covered by forests (EEA, 2010). Such an important area of mountain forests plays an essential role in providing multiple ecosystem services to human beings. Amongst the most important ecosystem services, there are both provisioning ones, e.g. timber production and regulating ones, e.g. biodiversity conservation, carbon sequestration and protection against natural hazards, such as rockfalls, shallow landslides and avalanches (MEA, 2005; EEA, 2010). Previous studies suggested that climate change can induce shifts in plant traits, biotic interactions, community structure and biome spatial repartition (Vogt-Schilb et al., 2015), all these characteristics being closely related to the ecosystem functioning and services. Mountain forests take part in one of the most vulnerable ecosystems undertaking these changes (Bugmann et al., 2005). Hence, it is important to judge if and until when the provisioning of ecosystem services can be maintained in the context of the ongoing climate change (Gonzalez et al., 2010; Elkin et al., 2013). In Europe, current projections suggest that air temperature may increase by at least 2 °C depending on the greenhouse gas emission scenario that is realized. A better understanding of the vulnerability of European mountain forest ecosystems is served as a primary and fundamental step for further optimizing forest management adapted to the climate changes.

Recent simulation based studies on European mountain forest have shown the powerful capacity to estimate the temporal evolution of the provisioning of different ecosystem services. Usually at local scales i.e. stand or landscape scales, they have evidenced a significant loss of provision of ecosystem services due to the climate change (Theurillat and Guisan, 2001; Bugmann et al., 2005; Elkin et al., 2013), which is, nevertheless, heterogeneous in space (Engleret al., 2011; Gottfried et al., 2012; Elkin et al., 2013). This heterogeneity may be attributed to two aspects: firstly, mountain forests situated at different regions might be exposed to different levels of climate change severity; then, mountain forests differing in abiotic (e.g. climatic, topographic, edaphic) and biotic (e.g. species composition, disturbance and colonization history), and anthropological (management and cultural regimes) conditions may possess different resistance and resilience against the climate changes. However, conclusions from these different case studies are difficult to be generalized or compared, as existing studies did not use the same management regimes, ecosystem service indicators and climate change scenarios. General trends based on cross site comparisons over large geographical scales still remain scarce. Business-as-usual conditions forest management scenarios have been widely and commonly applied for mountain forests in many European countries (Briceno-Elizondo and Lexer, 2004). However, little is known to which degree the business-as-usual scenarios are vulnerable to the climate change. Clarifying the main differences and the common trends of ecosystem services responses at large spatial scales would be highly useful to develop management guidelines for forest adaptation to climate change at the European level. .

The ARANGE project (www.arange-project.eu/) provides a valuable opportunity for ecosystem service comparison across multiple case study sites from different countries over Europe. It dealt with six case study areas in six European countries from west to east according to elevation: Spain, France, Austria, Slovenia, Slovakia, and Bulgaria, which are ecologically and climatically substantially different from each other. All case study areas applied the same protocol in term of forest characteristics and forest management data collection and simulations based on business-as-usual scenarios. The simulations performed within each case study area were performed at a finer spatial and ecological grain, thereby allowing more insight into climate change response mechanisms. For each case study area, using individual-based models integrating management and climate effects on demography explictly, we simulated the temporal dynamics of indicators concerning the four types of ecosystem services mentioned above (i.e. timber production, biodiversity conservation, carbon sequestration and protection against natural hazards). Forest simulations were done using both the baseline climate scenarios (i.e. null effect of climate warming, control factor) and five climate change scenarios derived using five different regional climate models that were driven by the A1B greenhouse gas emission scenario (IPCC 2007).

By statistically based comparisons between the evolution curves of ES of the climate change scenarios with the one of control scenario, we aims to address the following questions for each type of ecosystem services:

- **Q1**: Does the risk of climate change disrupting forest ecosystem service provisioning differ between climate change scenarios and case study areas?
- **Q2**: Does the timing of high climate change impact on forest ecosystem service provisioning differ between case study areas?
- **Q3**: What are the influence of management options, initial stand conditions and abiotic factors, and are they congruent between case study areas?

For (**Q1**), a null hypothesis may be that more southern and more continental case study areas, that currently exhibit warmer and drier climatic conditions, are relatively more at risk under future climate scenarios. Conversely, an alternative hypothesis may be that case study areas that are currently warmer and drier, may be less impacted by climate change as the forests are composed of more drought resistant species, thereby making them more pre-adapted to climate change. For the (**Q2**), we expect linear trends of both climate change scenarios and timing as our null hypothesis. For **(Q3)**, we might expect less vulnerable stands for mixed, less dense and uneven-aged stands.

Finally, we aim to address one question amongst indicators belonging to the four types of ecosystem services:

- **Q4**: whether some indicators or some types of ecosystem services are projected to be more sensitive to climate change, and whether or not this sensitivity bias is consistent across case study areas.

2 MATERIALS AND METHODS

2.1 Overview of case study areas

Six case study areas (CSA) were evaluated: CSA 1 – Montes Valsain (Spain), CSA 2 – Vercors (France), CSA 3 – Montafon (Austria), CSA 4 – Sneznik (Slovenia), CSA 5 – Kozie chrbty (Slovakia) and CSA 6 – Shiroka laka (Bulgaria). These CSA encompass longitude -4 °E to 25 °E, crossing the western-central European continent (Fig. 1). Within each case study area, a series of representative forest stands differing in altitudes, slope, exposition, forest structure, soil characteristics and management regimes were selected for intra-case study area studies. The representative stand, representing a forest area of several hectares, is the smallest unit used in our analyses. A brief summary of the representative stands is available in Table 1 and for more detailed information.

The case study areas differ remarkably in annual mean air temperature (°C) and annual precipitation (mm y^{-1}) (Fig. 2). The driest and hottest sites can be found at Montes Valsain (Spain). These climatic data are considered baseline climate scenario by which simulations of ecosystem services are severed as control group compared to the climate change scenarios based simulations.

For all CSAs we compared two types of BAU forest management regimes: stands with even-aged forest management and stands with uneven-aged forest management. In terms of species composition, even-aged stands are either monospecific or mixed but uneven-aged stands were all mixed stands (Table 1). The two types of stands are unevenly distributed between CSAs due to different silvicultural tradition of each region or country (Table 1). Even-aged stands dominate CSA 1 (Spain), CSA 4 (Slovenia), CSA 5 (Slovakia), and CSA 6 (Bulgaria), whereas uneven-aged stands dominate CSA2 (France) CSA 3 (Austria) and CSA 4 (Slovenia). In the present study, statistical models were applied toward three pools: M1 – total data used; M2 – mixed stand data used; M3 – even-aged stand data used (Table 1). Comparing the coherence of statistical diagnostics enable us to identify whether the results were sufficiently generalized or variable between stand types.

2.2 Climate change scenarios

We used simulated air temperature, precipitation and solar radiation data using transient climate change scenarios until the year of 2100. These data were retrieved from the EU FP6 project ENSEMBLES (Hewitt and Griggs, 2004), which has conducted 15 highly resolved (~25 km grid spacing) regional climate model simulations until the end of the 21t century for the European continent. The simulations were driven by eight different global climate models employing the climate change scenario A1B (Nakicenovic et al., 2000). Because the baseline climate scenarios is scaled at each case study region for different altitudes, slopes and aspects, the ENSEMBLES simulation data were converted via a Quantile Mapping approach (Dobler and Ahrens, 2008; Piani et al., 2010; Themeßl et al., 2011) so that they are compatible with the baseline climate data. The uncertainty of model predict due to emission scenarios were unavailable and difficult to obtain, so we used the uncertainty due to use of 15 regional climate models. This choice may be the best compromise to representing the future uncertainty of natural variability. More detailed descriptions about the ENSEMBLES simuations and its use in the study is available at the official website of the project (www.ensembles-eu.org).

For each CSA, climate change scenarios were based on its baseline climatic conditions. Five climate change scenarios, hereafter named as C1 to C5 were used as inputs for ecosystem services simulations and then compared between themselves and with the baseline climate data. Temperature is projected to increase in all CSA under all climate scenarios (Fig. 2). Projected changes in precipitation are considerably more variable between climate models and between CSA, but there is a small general trend for reduced precipitation (Fig. 2).

2.3 Forest simulations

2.3.1 Forest models

Forest dynamics of each CSA were simulated using one of three forest models PICUS; ForClim and SIBYLA (see for information). As none of the models possess parameters calibrated for all the CSA sites and species, we chose the most adapted model for simulations for each CSA instead of a single model for all the CSAs. PICUS was used for the CSA 1 (Spain), 3 (Austria) and 6 (Bulgaria). ForClim was used for the CSA2 (France) and 4 (Slovenia). SIBYLA was used for the CSA 5 (Slovakia). These mechanistic individual-based models have been widely applied in other case studies and were found to produce good and reliable results at either the stand level or landscape levels. When one of the above models was used for forest dynamics simulation for a CSA, the model parameters were calibrated for either local species or sites.

2.3.2 Forest stand initialization and simulated forest management

The initial state of all simulated forest stands was derived based on empirical stand data from each case study region that included DBH distributions, height-diameter relationships for individual tree species and regeneration abundance for each species.

Business as usual (BAU) forest management was implemented throughout the simulation period (100 years: 2010-2110). Each CSA provided detailed information on current RST management plans that included timing of management actions (tending, thinning, harvesting) and the size, species and volume of trees to be removed during each entry.

2.4 Ecosystem Service Indicators (ESI)

Indicators that evaluate the provisioning of ecosystem services can be either direct metrics (e.g. timber production) or indirect proxies. For cross-CSA comparisons, we chose the indicators that (i) can be calculated by all the forest models and (ii) have been well defined and routinely used in literature. Based on the above criteria, eight representative indicators were chosen for the four types of ecosystem services. For timber production, we used the cumulative volume of harvested timber of the total species and tree diameter classes of a stand by the investigated year (in m^3 ha^{-1}, Sterba et al., 2006). For carbon storage, we used the dry mass of carbon contained in above ground living tree biomass, including bole, branches, leaves of living trees (in t ha^{-1}, IPCC, 2006; Vallet et al. 2006). For biodiversity conservation, we chose the following three indicators: dead wood volume (in m^3 ha^{-1}, Grove, S.J. 2002; Lassauce et al., 2011), equivalent number of species, defined as tree species richness when all species in the stand share the same abundance (Jost 2006) and the true species diversity index related to the Shannon entropy index for tree species, defined as the equivalent number of species in a stand (Neuman and Starlinger, 2001, Jost 2006). For protection against natural hazards, we used two indicators referring to different hazards: rockfall protection index (dimensionless, Berger and Dorren, 2007) and forest cover (dimensionless) as erosion and landslide protection index. More detailed items on the justification and the calculation of these indicators can be found in Cordonnier et al. (2014).

2.5 Data processing and statistical analysis

2.5.1 Data normalization of ecosystem service indicators across CSA

To evaluate climate change impacts across CSAs we calculated the normalized relative change of each ecosystem service indicator. Within each CSA the average ecosystem service value, calculated across independent simulation replicated, realized for each year (t) between 2010 and 2100 under the baseline climate projections (C0) was used as the base value ($ES_{t,C0}$). For each stand in a CSA, the relative change in each ecosystem service indicator under each of the climate scenarios was calculated as:

$$\Delta ES_{t,Cx} = \frac{ES_{t,Cx} - ES_{t,C0}}{\max(ES_{t,C0})_{t\in[2001,2100]} - \min(ES_{t,C0})_{t\in[2001,2100]}} \qquad Eq.(1)$$

Where, $\Delta ES_{t,Cx}$ is change in each ecosystem service indicator at the year of *t* under the climate change scenario C*x* ($x \in [1,5]$); $ES_{t,Cx}$ and $ES_{t,C0}$ are the values of an ecosystem service indicator at the year of *t* under the climate change scenario C*x* and the baselines scenario (i.e. C0). The denominator represented the current system variability (Elkin et al. 2013), and is calculated as the maximum minus the minimum value of the ecosystem service indicator along the whole century.

2.5.2 Qualitative metrics indicating ecosystem service changes

The quantitative time series metric $\Delta ES_{t,Cx}$ do not usually follow normal distribution, thus preventing the direct application of Gaussian family linear regressions. To overcome this constraint, we introduced a qualitative metric, named “status,” to define changes in ecosystem services. We defined that (i) if $\Delta ES_{t,Cx}$ is -10% or less, the ecosystem service at the year t exhibits a significant loss of ES provisioning (in red colour), (ii) if $\Delta ES_{t,Cx}$ is 10% or greater, the ecosystem service at the year t exhibits a significant gain of provisioning (in green colour) and finally (iii) if the $\Delta ES_{t,Cx}$ is between -10% (included) and 10% (included), the ecosystem service at the year t is not significantly impacted (in grey colour).

2.5.3 Logistic regressions

Two types of logistic regressions were applied for analyzing the evolution of qualitative status which have three levels: red, grey and green. Firstly, we used a two-level logistic model (Freedman 2009) to fit the occurrence of red status against non-red status. Then, we used a three-level multinomial logistic model (Greene 1993) to fit the occurrence of red and green status against the grey status, respectively.

All the statistical analyses were performed using the R 2.13.0 (R Core Team, 2013).

3 RESULTS

3.1 Effect of climate change scenarios on ESs

The proportion of RST with diminished ecosystem services (in red) increased with increasing severity of climate change and through time (Fig. 3), but for many ES there was also an increase in the proportion of RST that improved ES indicators (in green). However, for all ES, except dead wood volume, there was a net reduction in ES at a CSA level (Fig. 3). The most moderate (c1) and sever (c5) scenarios caused the lowest and highest proportion of loss (red) and gain (green), respectively.

Climate induced changes in ecosystem services differed considerably between the CSAs. Under scenario c5, nearly all ecosystem services are projected to either increase or decrease in the France, Austria and Bulgaria CSAs by 2081-2100 (Figs. 4b, 4c and 4f). In contrast, shifts in ES levels are projected to be moderate in the Slovakia and Slovenia CSAs, and slight in Spain (Figs. 4a, 4b and 4e). Within each CSA, the RST that shifted from grey to red/green were not usually the same one for all the types of ecosystem services (Fig. 4). In a non-ignorable quantity of RST, more than five indicators of seven have changed their colour to red. However, there is no clear tendency that, if a RST is in loss of one or certain ecosystem service, all types of services are simultaneously degraded.

3.2 Effect of abiotic and biotic factors on ESs based on two-level logistical regressions

Cross-CSA statistical analyses found that the baseline climatic conditions (air temperature and precipitation) of each CSA is a good predictor of whether ES levels are projected to change, but the direction of change differed depending on the ES being examined (Fig. 5). Regardless of stand types, CSAs with higher air temperature and higher precipitation tended to generally promote the ecosystem service of production, carbon storage and protection. The three indicators of biodiversity conservation traded off between climatic conditions (Fig. 5).

Climate changes inducing changes in air temperature and precipitation modified the odds of loss of ecosystem services in contrasted manners (Fig. 5). Most of ecosystem service indicators increased with increasing temperature and with decreasing precipitation, except for the two indicators of biodiversity conservation: the dead wood volume and equivalent number of species, which had non-significant shifts (Fig. 5). Initial forest conditions, such as basal area had no significant effect on changes of most of ecosystem service indicators, except a slight beneficial effect on cumulative volume of harvest timbers (Fig. 5, zone of M1). The percentage of broadleaves had comprehensive effects on the biodiversity conservation service: it slightly favored dead wood volume, but leaded to a decline of equivalent number of species and Shannon's entropy index. Compared to monospecific stands, mixed stands could not effectively promote the biodiversity conversation; on the contrary, it could result in loss of the ecosystem services of production, carbon sequestration and protection (Fig. 5, zone of M1 and M3). Compared to even-aged stands, uneven-aged ones could significantly favor dead wood volume but decreased the other indicators (Fig. 5, zone of M2).

4 DISCUSSION

4.1 Shift of ecosystem services does not always show consistency in CSAs

Shift of ES were highly dependent on CSAs. Amongst the six CSA, ES shift in Spain was the slightest. This is due to the relatively high temperature and drought of the baseline temperature in Spain. Logically, climate change in Spain will bring a limited shift in ES provisioning. Compared to Spain, the two CSA in the Alps Mountains (France and Austria) seems to be profoundly impacted by climate changes. In the two CSAs, almost all the RSTs are subject to a radical shift in ES provisioning: provisioning, protective and carbon sequestration ES were all in decline. The ES shifts in gain are restricted into the indicators of biodiversity conservation. It is important to point out that the increase in biodiversity at a site should not be always considered a positive sign, as it may signify the migration of species from other zones and this may lead to irreversible loss of indigenous species. The Alps Mountains should be one of the most vulnerable European regions suffering from the loss of ES.

The three CSAs in East Europe are within the intermediate cases between Spain and the Alps Mountain sites. All the three CSAs exhibited a general ES shift toward the loss. However, the loss of ES type differs amongst them: CSA4 – Slovenia tended to drastically loss the protection ES; CSA 5- Slovakia tended to drastically loss carbon sequestration and production. CSA6- Bulgaria tended to loss all the service, but maintained well the equivalent number of species.

Overall, shift of ecosystem services does not always show consistency in CSAs. The baseline climatic conditions of RSTs (temperature and precipitation) could significantly explain the shift tendency of the majority of the investigated indicators of the ES, but in a complex way. This signifies that forest management should be specific at the CSA level, instead of the European level.

4.2 Vulnerability of ES is significantly dependent on climate change scenarios.

Previous studies have shown that the ecosystem services provided by forests are susceptible to climate changes (Elkin et al., 2013). In most cases, several ecosystem services show significant declining trend, suggesting that the provisioning of these services cannot be guaranteed by the end of this century (Elkin et al., 2013). In our study, on one side, we confirmed this high sensitivity of all the tested ecosystem services to climate changes factors (temperature and precipitation changes); on the other side, we showed that this shift could result in both a gain and a loss of ES at the global scale. Non-exceptionally, the scenario C5, the most thermally and hydrologically catastrophic scenario, resulted in a most important changes in CS provisioning. After the C5, the scenarios C2 generally resulted in more important changes in CS provisioning than C3 and C4, the two having more increase in temperature. This is probably due to the relatively lower precipitation in C2. With increasing temperature, an increasing quantity of precipitation may improve the resistance of ES shifts. The Logistic regression showed also a net negative effect of warmer temperature and a generally positive effect of more precipitation on the maintaining of ES, confirming this assumption.

The scenario C1, which leaded to the most moderate ES provisioning shift would be considered the relatively ideal of our future effort in climate change mitigation. Nevertheless, it is to be noted that even the moderate scenario cannot insure a stable provisioning of all the services by the end of this century. This is especially true with regard to the SE of biodiversity: three investigated indicators have already a high proportion of sites under C1 in the period of 2081-2100. This highlights, again, the high vulnerability of biodiversity as tremendous studies have previously revealed. The consequence of the loss of biodiversity of indigenous species is represented in multiple aspects. Accordingly, the current business-as-usual scenarios seem to be less adapted in biodiversity conservation. In the future, adopting alternative managements in some plots with more consciousness on biodiversity conservation might be a complementary approach to the BAU management

4.3 ES shift is temporally heterogeneous

Within the first 40 years can be considered a relative safe stage, since the proportion of sites where ES provisioning shift increased slowly. From the third 20-year period, the proportion of sites where the shift in ES provisioning was projected to be either in gain or in loss increased in a pronounced number but in generally linear manner. The vulnerability of ecosystem services differs greatly between ecosystem services. Increasingly, except C1, almost all the other scenarios terminate this safe stage at the same period. This tendency can also be reflected in the evolution curves in each RST. Climate change does not have an instantaneous effect, but become very destructive in mid and long term after a cumulative stage. Accordingly, the first 20-40 years may thus be considered a "buffer stage" in which human beings should make the most effort to prevent the occurrence of the ES shift.

4.4 Biological factors take only secondary effects

The investigated biological factors, including forest initial density and percentage of broadleaves could sporadically influence the shift in ES provisioning. However, in general, their effects remain secondary compared to the climatic factors.

Comparing the shift in ES provisioning between mixed and even-aged stands is a challenging work. This is partially due to the fact that the disparity between mixed and even-aged forest was masked by the disparity in baseline climatic conditions. However, we still succeed in evidencing that the climate changes factors have almost the same effect on both mixed and even-aged stands in a global trend. Through this cross-site analysis, we did not find any obvious evidence that supports the conventionally accepted hypothesis that mixed forests have better resistance toward the climate changes than even-aged stands. Accordingly, this is not in agreement with previous studies on local sites.

With regard to the interaction effect between the biological factors and forest stand type, both accordance and disparity co-exists depending on the type of ES, revealing a convoluted case when multiple factors take effect.

5 CONCLUSION AND PERSPECTIVES

Using individual based forest dynamics models, we estimated and compared the evolution of four types of ecosystems services (timber production, carbon stock, biodiversity conservation and protection against natural hazards) of mountain forest stands under current management, in case study areas from six European countries for 100 years. Despite a strong effect of case study area, the impact of climate change on ecosystem service followed rather similar trends in the different case studies areas. Yet, the impact could be significantly moderated by climatic conditions of each study site. Overall, this study suggests that the current forest management in Europe might not be safe enough for stable ecosystem services provision in the future.

References

Berger, F., Dorren, L. 2007. Principle of the tool Rockfor.net for quantifying the rockfall hazard below a protection forest. Schweiz Z Forstwes 158(6): 157-165

Briceno-Elizondo, E., Lexer, M.J., 2004. Estimating carbon sequestration in the wood products pool: model adaptation and application for Austrian conditions. Cent.bl. gesamte Forstwes. 121 (2), 99–119.

Bugmann H, Zierl B, Schumacher S (2005) Projecting the impacts of climate change on mountain forests and landscapes. In: Global Change and Mountain Regions (eds Huber UM, Bugmann HKM, Reasoner MA), pp. 1–11. Springer, Netherlands.

Dorren, L., Berger, F., Jonsson, M., Krautblatter, M., 2007. State of the art in rockfall forest interactions. Schweizerische Zeitschrift für Forstwesen 158, 128–141.

EEA (2010) Eurpoe’s Ecological Backbone: Recognising the True Value of Our Mountains. EEA Report, Copenhagen.

Elkin C, Gutiérrez AG, Leuzinger S, Manusch C, Temperli C, Rasche L, Bugmann H 2013 A 2 °C warmer world is not safe for ecosystem services in the European Alps.Glob Chang Biol. 2013 19(6):1827-40,

David A. Freedman (2009). Statistical Models: Theory and Practice. Cambridge University Press. p. 128.

Führer, E., 2000. Forests function, ecosystem stability and management. For. Ecol. Manage. 32, 29–38.

Greene, William H., Econometric Analysis, fifth edition, Prentice Hall, 1993: 720-723.

Grove, S.J. 2002. Tree basal area and dead wood as surrogate indicators of saproxylic insect faunal integrity: a case study from the Australian lowland tropics. Ecological Indicators 1: 171-88.2.4.2 Carbon storage

IPCC Guidelines for National Greenhouse Gas Inventories. 2006. http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html

Jost, L. 2006. Entropy and diversity. Oikos 113: 363–375.

Lassauce, A., Paillet, Y., Jactel, H., Bouget, C. 2011. Deadwood as a surrogate for forest biodiversity: Meta-analysis of correlations between deadwood volume and species richness of saproxylic organisms. Ecological Indicators 11: 1027-1039.

Neumann, M., Starlinger, F. 2001. The significance of different indices for stand structure and diversity in forests Forest Ecology and management 145: 91-106.

Sterba, H., Vospernik, S., Söderbergh, I., Ledermann, T. 2006. Harvesting Rules and Modules for Predicting Commercial Timber Assortments. In: Hasenauer H. (ed.), Sustainable forest management – growth models for Europe. Springer, Berlin a.o., 111-129.

Stokes A, Atger C, Bengough AG, Fourcaud T, Sidle RC. 2009. Desirable plant root traits for protecting natural and engineered slopes against landslides. Plant and Soil 324:1–30.

Theurillat JP, Guisan A. (2001). Potential impact of climate change on vegetation in the European Alps: a review. Climatic Change 50:77–109.

Vallet, P., Dhôte, J.-F., Moguédec, G.L., Ravart, M., Pignard, G. 2006. Development of total aboveground volume equations for seven important forest tree species in France. Forest Ecology and Management 229: 98-110.

Tables

Table 1 Repartition of sites in each forest stand type, case study area and models of regression.

Type of forest stand	Case study area							Model		
	1 - Spain	2- France	3- Austria	4 - Slovenia	5 - Slovakia	6 - Bulgaria	Total	M1	M2	M3
Even-aged monospecific stand	14	0	0	0	1	8	23	23		23
Even-aged mixed stand	0	0	0	26	43	12	81	81	81	81
Uneven-aged mixed stand	6	18	21	11	0	0	56	56	56	
Total	20	18	21	37	44	20	160	160	137	104

Note: For the models of regressions: M1 – total data used; M2 – mixed stand data used; M3 – even-aged stand data used.

Figures

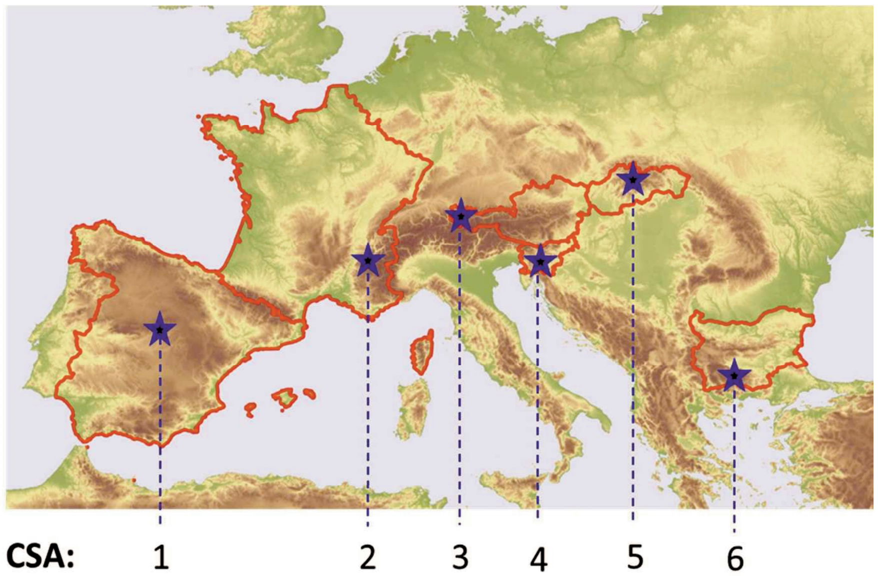

Figure 1 Geographic repartition of the six case study areas (CSAs). CSA 1 – Montes Valsain (Spain), CSA 2 – Belledonne (France), CSA 3 – Montafon (Austria), CSA 4 – Sneznik (Slovenia), CSA 5 – Kozie chrbty (Slovakia) and CSA 6 – Shiroka laka (Bulgaria).

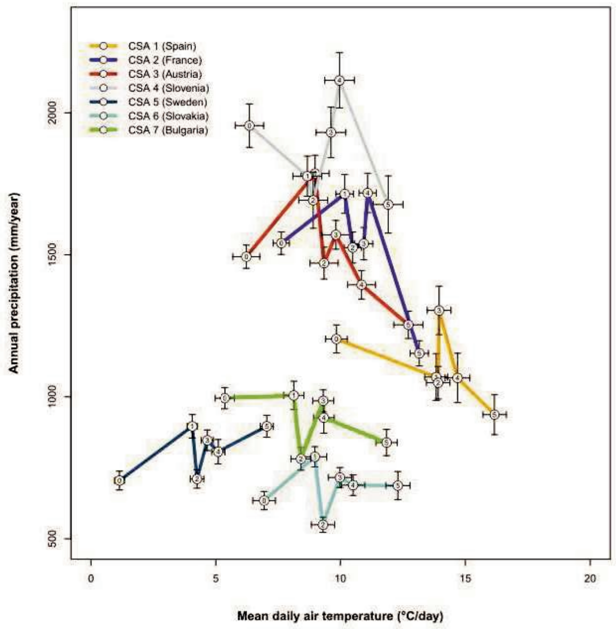

Figure 2 Comparison of the simulated climatic data of 2081-2100 between the six Case Study Areas (CSAs) of ARANGE. Data of all the months included. For each curve, the number in the circle denote the order of temperature from 0 (baseline scenario) to 5 (the most thermally catastrophic scenario). Error bars denote 1.96 ×stand error.

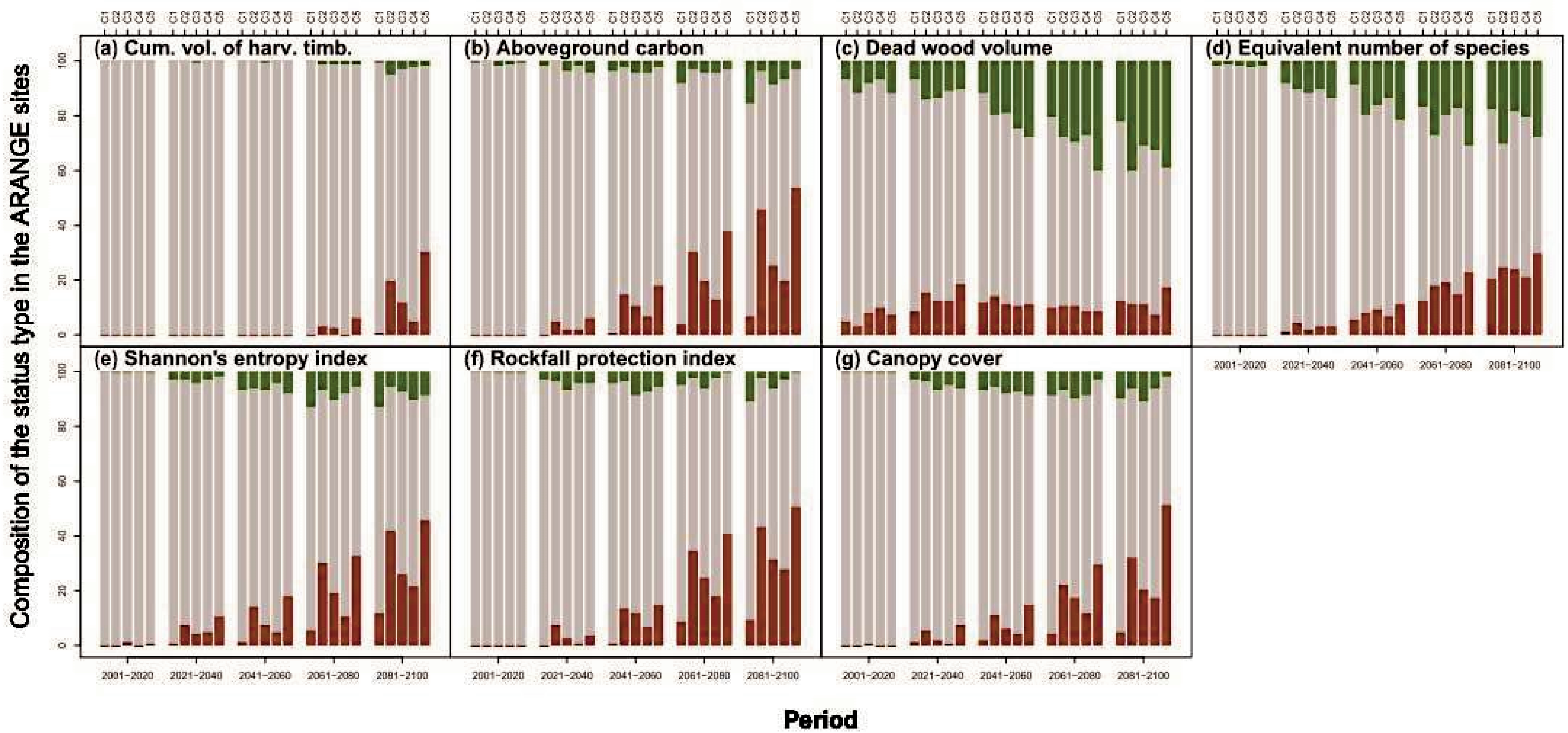

Figure 3 Effect of period and climate change scenarios on the composition of the status type in the ARANGE case study areas for the investigated ecosystem services. The three colours represent the three status of services defined in Section 2.5.2: green – gain of service, grey – maintaining of service, red –loss of services.

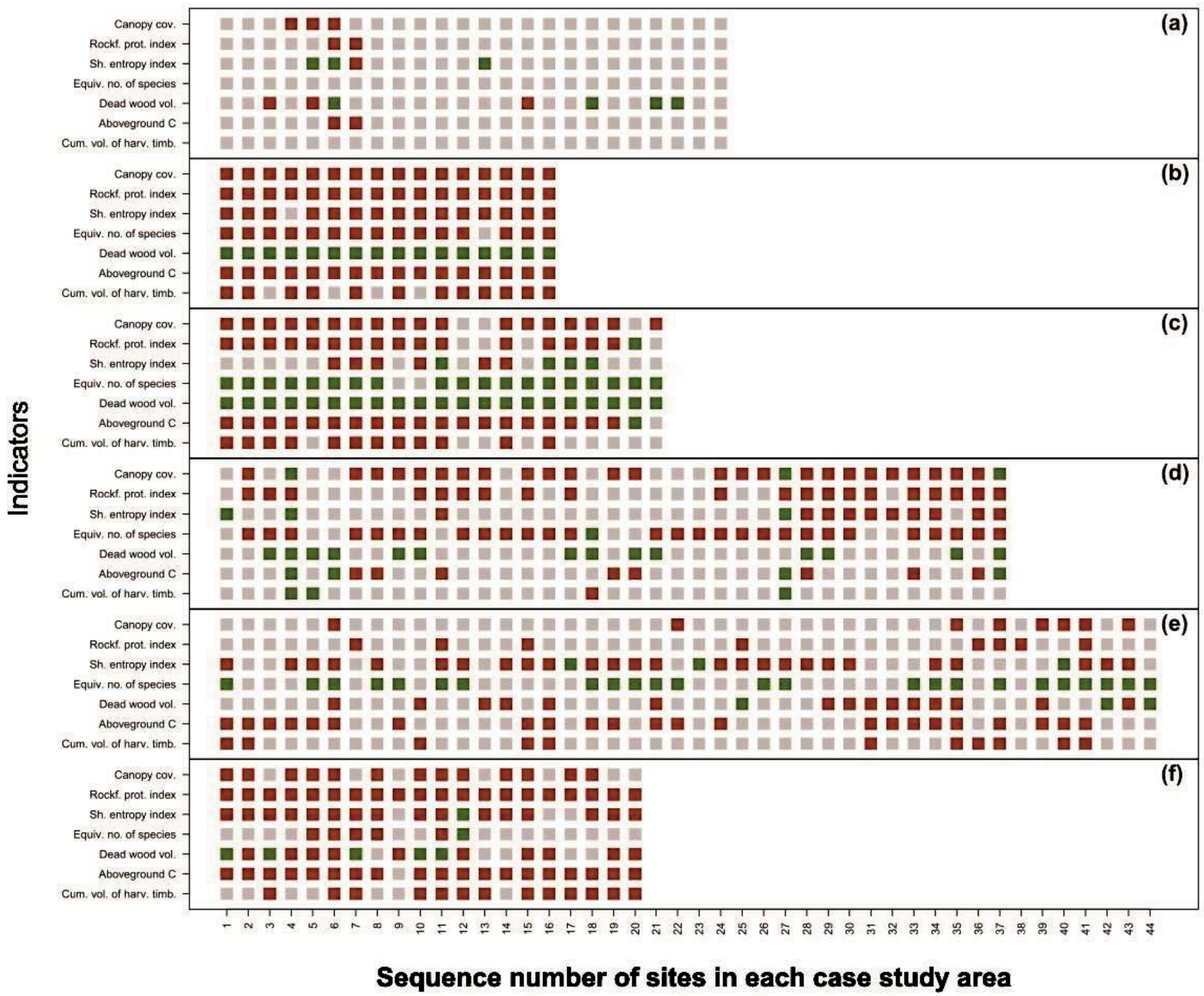

Figure 4 Distribution of status types of services in each of the case study areas. This figure is generated based on the climate change scenario 5 and the period 2081 to 2100. The three colours represent the three status of ecosystem services defined in Section 2.5.2: green – gain, grey – maintaining, red –loss.

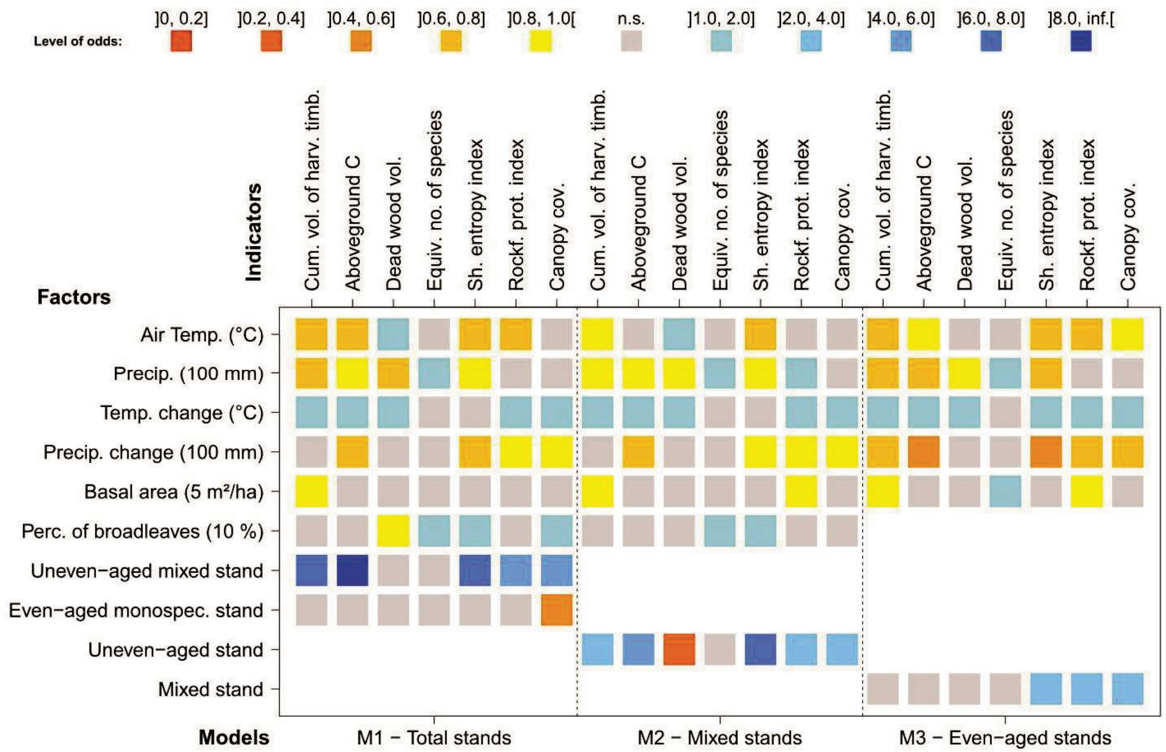

Figure 5 Effect of site climate, climate change and forest characteristics on the vulnerability of ecosystem services based on the two-level logistic regressions. The colours represent the odds. Amongst the factors (*y*-axis), those with units in parentheses are quantitative factors and the remaining ones are qualitative ones. Given an odd value A, it should be interpreted as follows: A times occurrence of risk with increasing one unit (i.e. the case of a quantitative factor) and compared to the reference class (i.e. the case of a qualitative factor). Only the case of the period of 2081-2100 is shown.

Regional Environmental Change

Can the current management regime maintain multifunctionality in an Alpine forest landscape under conditions of climate change

--Manuscript Draft--

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Corresponding Author:	Florian Irauschek Universitat fur Bodenkultur Wien Vienna, Vienna AUSTRIA
Corresponding Author Secondary Information:	
Corresponding Author's Institution:	Universitat fur Bodenkultur Wien
Corresponding Author's Secondary Institution:	
First Author:	Florian Irauschek
First Author Secondary Information:	
Order of Authors:	Florian Irauschek
	Werner Rammer
	Manfred J. Lexer
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Can the current management regime maintain multifunctionality in an Alpine forest landscape under conditions of climate change

Irauschek*[1] F., Rammer[1] W., Lexer[1] MJ

[1] Institute of Silviculture, University of Natural Resources and Life Sciences, Vienna (BOKU), Peter-Jordan-Strasse 82, A-1190 Vienna, Austria

*Corresponding author

Abstract

In Central Europe management of forest resources for multiple ecosystem services (ES) has a long tradition and is currently drawing much attention due to increasing interest of stakeholders in non-timber services. In face of a changing climate and diverse ES portfolios a key issue for forest managers is to assess vulnerability of ES under current management regimes (BAU). In a case study catchment of 250ha in the Eastern Alps we analysed an uneven-aged BAU management regime based on irregularly shaped patch cuts along skyline corridors. Novel landscape assessment tools within the PICUS modelling software were employed to analyze (i) the future provisioning of timber, carbon sequestration, protection against gravitational hazards, and nature conservation values under BAU management, (ii) the effect of spatial resolution (1ha, 5ha, 10ha grain size) in mapping ES, and (iii) the multifunctionality of the emerging forest landscape. BAU management sacrificed timber harvests to the benefit of Carbon sequestration and bird habitat provisioning. A no-management regime (NOM) showed better performance in all non-timber ES. Strong warming and decrease in summer precipitation significantly reduced volume, carbon pools and large veteran trees, and increased standing deadwood due to an intensifying bark beetle disturbance regime. Bird habitat benefitted also from bark beetle disturbances. Despite favourable temperature conditions in climate change scenarios the share of admixed species was not increasing in BAU management, mainly due to the heavy browsing pressure by ungulates. In NOM it even decreased and mean tree age is increasing without initialization of regeneration. Thus, in the long run NOM may enter a phase of reduced ES provisioning and lower resilience compared to BAU. The share of multifunctional area in the landscape decreased with increasing number of considered ES. With increasing grain size the multifunctional area increased in general. Under moderate warming the multifunctional area increased compared to current climate, however, under strong warming the multifunctional area is reduced. In general, at reasonable performance levels, the non-timber ES in our analysis are neutral or even complementary over long time periods. Which implications intensified timber harvesting may have for other ES requires further analysis.

Keywords: mountain forests, ecosystem services, scale, assessment, PICUS, climate change, forest management

1 Introduction

Mountain regions provide a diverse range of ecosystem services (ES). In the Eastern Alps in Central Europe mountain forests serve as a source of timber to support the needs of industry as well as of fuel wood for subsistence use. Forests have to protect slopes from landslides and soil erosion and protect settlements and infrastructure against gravitational natural hazards like snow avalanches and rockfall (Malin and Maier 2007; Dorren et al. 2004). In Austria, for instance, 31% of forest area has been assigned such a protective role as top priority (Niese 2011). Regionally, this percentage may be as high as 66%. Due to close to nature status of mountain forests the share of nature protection areas, such as those under the EU Natura 2000 regulations, is particularly high in mountain areas. Recently, the provisioning of drinking water and the dampening of runoff peaks for hydropower production as well as Carbon sequestration have been recognized as key ecosystem services. The relevance of these ES in general and for specific stakeholder groups in particular may vary strongly from region to region (EEA 2010). This multitude of vital ES demands have led to the paradigm of multifunctional forestry where many ES have to be provided simultaneously at small scale (Nijnik et al. 2015). Forests are multifunctional by nature (Kaljonen et al. 2007). When ecosystem services are complementary or neutral integration may be a feasible approach (Raudsepp-Hearne et al. 2010). In case of conflicting ES, trade-offs must be considered and inefficient solutions may be the consequence (e.g. Jacobsen et al. 2013) if management concepts enforce integration at small scales (i.e. stand level, a few hectares). Zoning is then a typical approach to disentangle ES conflicts (Cote et al. 2010).

In recent years, the paradigm of landscape-level planning in forest management has evolved in European forestry (e.g., Fries et al. 1998). While in Scandinavian countries there is already ample experience in landscape level planning (e.g. Lamas and Eriksson 2003) in Central European forestry it has been seldomly implemented in practice so far. While local practical solutions to balance actual ES demands have been established ever since by managers and stakeholders, the paradigm of multifunctionality in general has been rarely touched in policymaking and governance (Suda and Pukall 2014).

Landscape level planning implies that (i) multi-scale processes such as disturbance regimes are considered in forest management, (ii) different ES may require different spatial scales for quantification and monitoring, and (ii) different ES or portfolios of ES may be prioritized in different parts of the landscape. A prerequisite for such approaches to manage for various ES is sound knowledge about the interrelatedness of different ES and how this may depend on forest management regimes and other drivers such as climate change. Planning across ownerships imposes particular challenges (Nijnik et al. 2010). Thus, in small-scale ownership structures integration of ES provisioning may be the only practical solution. Future climate change may impact ES differently (Seidl et al. 2007; Lindner et al. 2010; Hanewinkel et al. 2012), thus adding complexity to forest management decision making with the need to find new balances in ES provisioning. The issue of scale in ES provisioning has only recently attracted more attention in landscape ecology and landuse planning (e.g. Gret-Regamey et al. 2012; Wu et al. 2002; Raudsepp-Hearne et al. 2010). In forestry, however, the issue at which spatial scale the provision of specific ES portfolios is feasible and under which conditions this may be economically efficient is still a matter of debate and calls for focused research.

Here we set out to assess a currently practiced unevenaged forest management regime in a catchment in the Eastern Alps in Austria under climate change conditions and evaluate impacts on ES (timber production, carbon sequestration, nature conservation values and protection against snow avalanches, landslides and erosion). We used the forest ecosystem model PICUS v1.5 with a recently developed landscape assessment tool (Maroschek et al. 2014).

We were particularly interested in (a) the spatial pattern of ES provisioning and multifunctionality, and how this develops over time; and (b) how the spatial scale of ES assessment (i.e. grain size) affects multi-functionality in a mountain forest landscape.

2 Methods & material

2.1 Study area

The study area is located in the Province of Vorarlberg in Austria, close to the Swiss border in the Rellstal valley (N 47.08°, E 9.82°). Landowner is the Stand Montafon Forstfonds (SMF), which owns about 6.500 ha forest land in total. Depending on bedrock the soils are composed of rendzinas and rankers, as well as rich cambisols and podzols. The terrain is steep, with slope angles from 30-45°, which makes management difficult and underlines the protective function against gravitational natural hazards. The case study area is a catchment of 250ha total area (234 ha forest area) in the upper part of the valley at altitudes between 1060 m and 1800 m (a.s.l.). The timber line has been strongly shaped by human activities such as livestock grazing and alpine pasturing. During the last decades, those activities have been widely regulated, and since then grazing has been abandoned in the study area (Malin and Maier 2007).

In this region, forest management has been practiced since more than 500 years (Bußjaeger 2007). The management objectives of the SMF are income generation from timber production, securing sustainable protection against snow avalanches and landslides (Malin and Lerch 2007). In addition, major shares of the forest area are under Natura 2000 regulations with a focus on bird habitat protection for European Green Woodpecker (*Picus viridis*), Black Woodpecker (*Dryocopus maritimus*), Great spotted Woodpecker (*Dendrocopus major*), Three-toed Woodpecker (*Picoides tridactylus*) and Eurasian Treecreeper (*Certhia familiaris*) (Grabherr 2000).

2.2 Forest

The vegetation belts in the study region range from the submontane up to the nival zone. The actual timberline is located at approximately 1800 to 2000 m a.s.l. depending on the local climatic and edaphic conditions. The forests are dominated by Norway spruce (*Picea abies*, 96% of growing stock) with minor shares of silver fir (*Abies alba*, 3%), European beech (*Fagus sylvatica*, 1.6 %) and other broadleaved species (e.g., *Acer pseudoplatanus, Fraxinus excelsior*, 1%). Due to the low management intensity, there is a significant share of large old trees. Productivity ranges from 3.5 to 12 $m^3ha^{-1}year^{-1}$ depending on site and stand composition and structure. The current mean standing stock in the case study area is 455 m^3ha^{-1}. The largest part of the forest is located on steep slopes and requires skyline based harvesting systems for timber extraction.

2.3 Climate data

A baseline climate (c0) and five transient climate change scenarios (c1 to c5), each consisting of a 100-year time series covering the period 2010-2110 of daily temperature, precipitation, radiation and vapor pressure deficit, were prepared for the model simulations. The baseline climate was generated from available daily instrumental data of the historical period 1961-1990 from the meteorological station Feldkirch (9.6° long, 47.27° lat), and adjusted for representative site types within the case study area regarding altitude, slope and aspect using the algorithms in Thornton and Running (1999). The five climate change scenarios were based on regional climate simulations from the ENSEMBLES project (Hewitt and Griggs 2004; www.ensembleseu.org). For details on the downscaling approach see Bugmann et al. (this volume). Mean historic climate at 1000 m a.s.l. is 6.2°C MAT and 1150mm annual precipitation with 840mm during summer season from May to September. In all climate change scenarios temperature increased (+2.6°C in c1, +3.0°C in c2, +3.5°C in c3, +4.3°C in c4, +6.0°C in c5). In all climate change scenarios except c1 there was a relative shift of precipitation from summer (May-September) to winter with -7% in c2, -32% in c3, -19% in c4 and -14% in c5. Anomalies were all related to periods 1961-90 and 2071-2100.

2.4 The PICUS forest ecosystem model

The model used for this study is the hybrid (sensu Peng 2000) forest ecosystem model PICUS v1.5. The model is a hybrid of classical gap model components (PICUS v1.2, Lexer and Hönninger 2001) and process-based stand-level NPP algorithms (3PG, Landsberg and Waring, 1997). A detailed description of the model is provided in Seidl et al. (2005). Here, just a brief overview on the core model concept is given.

PICUS simulates individual trees on a regular grid of 10 x 10 m² patches. The leaf biomass of trees is arranged in crown cells with a vertical resolution of 5 m. A three-dimensional light model, allowing for the explicit consideration of direct and diffuse radiation within the canopy, is used to model inter and intra tree species competition. Stand level productivity is estimated with a simplified model of radiation interception and light use efficiency (Landsberg and Waring, 1997) which depends on temperature, precipitation, radiation, vapor pressure deficit, soil water, and nutrient supply. Redistribution of assimilates to individual trees, assuming fixed respiration rates (Landsberg and Waring, 1997), is accomplished according to the relative competitive success of the individuals within the patch environment context (see Lexer and Hönninger, 2001). The tree regeneration layer dynamics are modeled within five height classes (Woltjer et al., 2008). The PICUS model furthermore includes the TRACE soil module as described in Seidl et al. (2008) which in the current study was used to simulate C cycling through the ecosystem as a prerequisite to monitor effects of management and climate on the soil C pools. Dead trees, if not removed through forest management, are transferred stochastically from snags to wood detrital pools on the forest floor. The PICUS model includes also a bark beetle disturbance module which (i) computes the stochastic infestation risk for simulated forest stands, (ii) estimates the damage intensity if an infestation occurs, and (iii) distributes the resulting tree mortality within the simulated stand.

PICUS contains a flexible management module based on a scripting language allowing for spatially explicit harvesting interventions as well as planting operations at the level of the 100 m^2 patches. The basic time-step of the simulation is monthly with annual integration of the tree population dynamics processes. The model requires information about the soil water storage capacity, the pH value of the mineral soil as well as plant-available nitrogen as a proxy for nutrient supply and a number of soil process parameters which for the site types in the case study area were taken from the soil data base by Seidl et al. (2009). The PICUS model in the current study was driven by monthly values of temperature, precipitation, solar radiation and vapor pressure deficit of the atmosphere.

Maroschek et al. (2014) describe a newly developed approach to initialize forest state for a PICUS simulation from the combined use of forest inventory data (DBH distributions, height-diameter curves, regeneration) and remote sensing based information (volume map, normalized crown surface model). Forest stands at tree level resolution of up to 20ha size can be initialized and simulated simultaneously. In a yearly resolution single tree maps can be exported and loaded into a landscape assessment tool (LAT). The LAT can visualize and analyse multiple single tree maps on a digital terrain model. Tree and standing dead wood attributes (coordinates, species, and dimension) can be analysed in freely selectable sub areas or with moving window approaches (see Maroschek et al. 2014) and exported for further analysis or enhanced visualization purposes.
PICUS has been tested extensively (e.g., Huber et al. 2013, Didion et al. 2009). Recent applications of the model to study mountain forest management include Seidl et al. (2010b), Seidl et al. (2011), Lexer and Seidl (2009) and Maroschek et al. (2014).

2.5 Forest initialization

Tree and stand data were acquired by terrestrial and aerial inventory methods. Based on polygons derived manually from arial images a terrestrial inventory was carried out, using angle-count sampling on a base raster of 50x50m, measuring at least 8 inventory plots per polygon to gather information about basal area shares and diameter distributions of tree species, and a description of tree regeneration and soil attributes. From Hollaus et al. (2006, 2007) a normalized crown model and a volume map based on high resolution LiDAR data was available. Based on this input data tree maps (size, species and location of individual trees) were generated for the polygons. For details of the approach see Maroschek et al. (2014).
The 250ha landscape was structured into 18 harvesting units (HU) which were populated with the polygon-based tree maps. These HUs were then used as basic entity for the model simulations (4-20 ha in size, Figure 1). The main rationale for the delineation of harvesting units is the efficient location of skylines (parallel or radial). With support of GIS-tools depending on the forest road network and on the shape of the meso-relief and interviews with forest staff, positions of 131 skylines where located to provide access to forest area.

2.6 Forest management

The current management regime (BAU) is aiming at unevenaged, structurally diverse forests. Due to steep terrain, harvesting operations are bound to motor-manual harvesting and long distance cable yarding with skyline systems. Skyline tracks typically extend diagonally across the slope to avoid vertical corridors which may favour avalanches and rockfall. The mean skyline length in BAU management over the 100 year analysis period is 534m (minimum 110m, maximum 955m). Current management features patch cuts along the skyline track with variable size and shape of the patches with a typical maximum width of 50m and a mean length of 40-50m along the skyline. Spacing and timing of the skylines depend on the maturity of forests and on the avoidance of negative visual impact by too intensive (locally clustered) skylines and related management interventions. Current management relies fully on natural regeneration. No tending and thinning operations are carried out in the rejuvenated patches. The aim is to maintain and further develop the heterogeneous uneven-aged forest structure. According to management records and as implemented in the BAU regime in this analysis each year approximately 0.4% of the forest area is subject to felling operations (0-2 skylines per year which corresponds to 0.83ha mean cutting area per year). This corresponds to a virtual rotation length of 250 years.

Due to current hunting and game management practices population densities of ungulates are high and as a consequence selective browsing pressure on admixed tree species is severe. Based on Maroschek (unpublished data) browsing probability in the model runs for Abies alba seedlings was set to 0.78, for Fraxinus excelsior 1.0, Acer pseudoplatanus 0.51 and Fagus sylvatica 0.70.

For comparison a no-management regime (NOM) without any active silvicultural intervention has also been simulated.

2.7 Analysis

Ecosystem service indicators

Table 1 shows the ecosystem service (ES) indicators used in the current study. For details on indicator definition see Bugmann et al. (this volume). The BHQ characterizes in three categories the habitat quality for bird species depending on structural attributes of the forest (standing large dimension deadwood, veteran trees, canopy cover) and occurrence of management activities. The avalanche protection index (API) indicates protection against snow avalanche release. The index was calculated using mean slope, basal area and average diameter. Landslide and erosion protection (LPI) builds on crown cover, defined by projected crown area for trees with DBH >5cm (compare also Frehner et al. 2005).

Assessment approach

BAU and NOM scenarios were each simulated under baseline climate and the five climate change scenarios and model output (tree level) was mapped into a DEM. ES indicators (see Table 1) were calculated from model output and provided as mean values for three 33-year periods. The flow indicators THV, VI and BBD were available for the HU as basic simulation entity only and aggregated at landscape level, state indicators were calculated for the HU, as well as the 1ha, 5ha and 10ha samples (i.e grain size; see Figure 2).

First, ES provisioning at landscape scale and how this was impacted by climate change is presented. For calculation of basic ES indicators the full landscape simulation (i.e. 18 harvest units as simulation entities) was used. The ES indicators BHQ, API and LPI required a local spatial context and were therefore calculated as mean value from the 1ha samples (see Figure 2).

Second, we tested the effect of grain size (i) in estimating ES provisioning, and (ii) on the spatial heterogeneity of ES indicators (i.e. the coefficient of variation of the ES estimate) in the landscape. The different grain sizes were also used to test for effects of analysis period and climate scenarios. ANOVA and Tukey tests were employed for continuous indicators, Friedman and Wilcoxon tests for categorical indicators.

Third, the joint provisioning of two, three and four ES at sufficient performance level (i.e. multifunctionality) was analyzed at different levels of spatial resolution.

3 Results

3.1 Ecosystem services at landscape level

Comparing BAU and NOM under current climate and climate change scenarios

Under current climate (c0) and BAU management standing stock increased from 437m^3ha^{-1} to 490m^3ha^{-1} (periodic mean in period P3) due to harvests remaining clearly below the periodic increment (mean TVH of 1.9 $m^3ha^{-1}yr^{-1}$ over the entire analysis period versus mean VI of 5.7 $m^3ha^{-1}yr^{-1}$). Also bark beetle induced tree mortality remained at relatively low level (0.5-0.65 $m^3ha^{-1}yr^{-1}$). Without harvests (NOM) volume increased to 600m^3ha^{-1} in P3. For details under current climate see Table 1. When forests are managed according to BAU the increment rates increased under climate change scenarios c1, c3 and c4, while in c2 and particularly in c5 productivity decreased (Figure 3) depending on the interplay of precipitation and temperature. In warmer climates damages from bark beetle disturbances increased more under the NOM regime (up to 522% in NOM under c5) and consequently standing stock decreased under all climate change scenarios (-15% in P3 under BAU management in climate c5) except under climate scenario c1 which resulted in slight increases in P3 under both BAU and NOM (Figure 3, Table 3).

Closely correlated with volume are in-situ Carbon pools which increased under BAU in current climate (c0). In the final assessment period P3 the NOM regime holds an additional amount of 30.2 t ha^{-1} compared to BAU (Table 1). From Figure 3 it is evident that under all climate change scenarios, except c1, total Carbon storage (CS) decreased (up to -6% under c5).

The shares of Silver fir and admixed broadleaved species were decreasing over time under all management and climate scenarios. This effect was stronger under the NOM regime. Results under climate scenario c0 are shown in Table 1.

In relative terms Silver fir and broadleaves could benefit from more favorable growing conditions under the warming scenarios under BAU as well as NOM. As a consequence, while tree species diversity (D) for the entire landscape was declining under current climate, it was increasing slightly under all climate change scenarios, strongest under scenarios c4 and c5 (Figure 3). The increase in admixed species share (not shown) as well as in the diversity indicator D was slightly smaller in the NOM scenario (Table 3). Due to regeneration fellings tree size diversity (H) increased under BAU in all climate scenarios (Table 1, Figure 3), while in NOM tree size diversity decreased slightly (not shown).

Under current climate the bird habitat quality index BHQ showed a shift towards *"moderate"* (category BHQ2) and *"good"* (BHQ3) habitat quality under BAU as well as NOM. The combined area shares in BHQ2 and BHQ3 increased under BAU from 49% in P1 to 64% in P3, under the NOM regime from 54% to 77% (Table 1). Under the warmer conditions of c1 and c5 these area shares increased to 68% and 83% (under BAU), and to 81% and 89% (NOM) respectively in period P3 (Table 3, Figure 4). Climate change scenarios, particularly scenario c5, favored habitat quality because of more available standing deadwood and canopy openings due to bark beetle damages. Without active management standing deadwood volume (SDWV) increased to 28.8m^3ha^{-1} (P3, current climate; Table 1). Climate change further increased SDWV by up to 51% (BAU under c5; compare Figure 3). Under NOM the number of large veteran trees (LLTN) increased under all climate scenarios except c5 where natural tree mortality and bark beetle infestations resulted in a decrease in LLTN. Under BAU harvests and bark beetle damages reduced LLTN (Table 1, Figure 3), the latter particularly under conditions of climate change (Table 3).

Landslide protection in the beginning of the simulation period was already well developed. In P1 under current climate and BAU management 93% of the area met the crown cover criterion for medium or good protection (Table 1; categories LPI2 and LPI3). This share rose to 98% in P3. Under the NOM regime these shares were even higher and in P3 amounted to 100%. The development was similar for protection against avalanches (API) (results under c0 in Table 1). Interestingly, both API and LPI were almost insensitive to climate change (Table 3).

3.2 Scale dependency of ecosystem service indicators

With three grain sizes we explored the effect of the assessment scale on ES estimates and spatial heterogeneity of ES indicators. ANOVA for effects of grain size within periods and management regimes under current climate were not significant (alpha = 0.05) for V, CS, D, SDVW, LLTN and API. For ordinal indicators (BHQ, LPI) nonparametric Friedman and Wilcoxon tests were employed. To meet the requirements of the Friedman test for BHQ and LPI 100 samples of 15 grid cells each were randomly drawn from the 1ha and 5ha pixels and compared to the 15 10ha cells. In general, the share of significant tests (alpha = 0.05) for effects of grain size was small, but larger under the NOM regime compared to BAU (both under current climate c0) and increased from P1 (BAU: 5% for BHQ, 1% for LPI; NOM: 6% for BHQ, 1% for LPI) to P3 (BAU: 11% for BHQ, 1% for LPI; NOM: 19% for BHQ, 8% for LPI). The 1ha grain size yielded less favourable results for BHQ as well as LPI. Significant grain size effects in the final assessment period P3 in three contrasting climate scenarios were more abundant under the NOM regime, however, no clear pattern resulted from the different climate scenarios. Wilcoxon tests clearly indicated that the 1ha grain size generated the least favourable results for BHQ and LPI. Figure 4 exemplifies such grain size effects. Summarizing, grain size effects on ES estimates were rather small or non-existent at all. Interestingly, the aggregate BHQ index (large snags, veteran trees, canopy cover) was most sensitive to the assessment scale.

In addition, we tested effects of time periods and of selected climate change scenarios with paired Wilcoxon tests. In general, there were rather few significant results for effects of time periods, most under NOM (compare section 3.1) when tested with 1ha grain size, indicating that V, SDWV, LLTN, API, LPI and BHQ increased with elapsing time (Table 2).In accordance with section 3.1 climate scenarios had significant effects on V, CS, SDWV with lowest V and CS and highest SDWV under scenario c5. BHQ showed a tendency towards more favourable values under climate scenario c5 (mainly under NOM regime) (Table 3).

In general, the variability of indicators expressed as coefficient of variation (CV) decreased with increasing grain size (see Figure 5). However, magnitude and temporal development of the variability differed among indicators. Not unexpectedly, LLTN varied greatly when sampled with 1ha squares, but the CV decreased in P2 and P3. Estimates of total carbon storage showed a decreasing CV over the three assessment periods almost independent of climate scenario. Tree species diversity showed very low contrasts between grain sizes and climate scenarios which is mainly due to the dominating role of Norway spruce. Admixed tree species are rare and do occur in spatial clusters depending on site conditions and regeneration fellings. Particularly the fellings along the skyline tracks initiate regeneration of Silver fir, mountain maple and beech which become effective in D in later decades of the assessment period. With small grain size these rare events are obviously missed in most samples which leads to low variation in D while with larger sample size admixed species were more frequently hit, thus increasing the CV in D, particularly under warming scenarios. Similarly, API is high throughout the landscape, resulting in a very low variation which even decreased further along time (Figure 5).

3.3 Grain size and multifunctionality

We decided to use Carbon storage (CS), bird habitat provision (BHQ) and protection against avalanches API) and landslides (LPI) to analyze the simultaneous provision of ecosystem services as these ES are represented unambiguously by one specific ES indicator. We categorized total Carbon storage (category CS1: <203 t/ha, CS2: 203-332 t/ha, CS3: <332 t/ha) and API (API1: 0-0.33, API2: 0.34-0.66, API3: 0.67-1.0) in three performance classes so that they were comparable with the ordinally scaled indicators BHQ and LPI. For each grain size the share of samples with two, three and four ES indicators being simultaneously rated at least *"moderately good"* (categories 2 or 3) was determined.

Figure 6 shows several distinct pattern for period P3 where effects of management as well as climate change scenarios became visible: (a) the tendency that the multifunctional area in the case study landscape decreased with increasing number of considered ES. This effect was particularly visible when moving from portfolios of two to three ES; (b) under the NOM regime the multifunctional area shares were not as strongly decreasing when more ES were demanded at small scale; (c) with increasing sample size (i.e. grain) the multifunctional area increased in general, and (d) BAU management could increase the multifunctional area under the moderate warming of scenario c1 (also having favourable distribution of summer precipitation), whereas under the severe climate change scenario c5 the multifunctional area was smaller compared to c1 and sometimes even lower than under current climate; (e) under the NOM regime climate change generally resulted in a fairly slight drecrease in multifunctional area.

In period P3 with two ES between 53% (CS and BHQ under c5 at 5ha grain size) and 100% (particularly the combined protective services against avalanches and landslides and erosion) of the landscape were considered as multifunctional. In the NOM scenario these shares increased to 76% (CS & BHQ, LPI & BHQ under all climate scenarios at 1ha grain size) and 100% (18 different ES combinations under all climate and grain size combinations). The multifunctional share of the landscape with three ES ranged from 53% (API, CS and BHQ under climate scenario c5 with 5ha grain size) to 86% (LPI, CS, BHQ under climate scenario c1 and 10ha grain size) under BAU management. In unmanaged conditions (NOM) the worst ES combination increased to 76% (LPI, CS, BHQ) and the best ES combination to 100% of the landscape area (all ES triplets under current climate and grain sizes larger 1ha), respectively. When four ES had to be integrated at small scale a minimum of 53% (5ha grain size, climate scenario c5) and a maximum of 86% (10ha grain size, climate scenario c1) of the managed landscape (BAU) were considered as multifunctional. NOM generated between 76% (under c0 and c5 at 1ha grain size) and 100% (under current climate c0 at 10ha grain size) of multifunctional landscape area.

Analysis of the temporal development of multifunctionality in the study landscape (climate c0) revealed that from periods P1 to P3 the area with sufficient ES provisioning increased with sample sizes of 1ha and 10ha, and decreased or showed no trend at all with 5ha grain size (not shown).

4 Discussion and conclusion

In the presented study we analyzed the current management practices and its effect on the provisioning of timber production, carbon sequestration, nature and habitat conservation and protection against gravitational hazards (avalanches, landslides and erosion) under current climate and five climate change scenarios in a catchment of 250ha in the Eastern Alps in Austria. Here we scrutinize the analysis approach, the ability of BAU management to provide the demanded ES, the spatial heterogeneity of ES indicators within the case study landscape and finally the level of integration in providing multiple ecosystem services from the same parcel of forest.

4.1 Analysis approach

The PICUS forest ecosystem model has already proven its ability as a workhorse for climate change impact studies (Maroschek et al. 2014, Seidl et al. 2011, Lexer et al. 2002). The model has been evaluated in several validation experiments and has built up substantial credibility for applications in European mountain forests (e.g. Huber et al. 2013, Didion et al. 2009, Seidl et al. 2005). In the current contribution the size of a simulation unit had been increased once more and is now at approx. 20ha simultaneously simulated forest area. This extent of the simulation entities allows a consistent implementation of felling regimes, disturbances including bark beetles and storms (see Pasztor et al. 2014a,b). Roces-Diaz et al. (2015) point at the importance of remote sensing data to (i) overcome the data bottleneck for ES assessments and (ii) to improve the spatial representation of ES supply. The employed forest initialization and projection approach in the current study supports both issues. The ability to map the trees from a set of simulation units into a digital terrain model offers huge potential to analyze structural and compositional features of a forested landscape (Maroschek et al. 2014). In the current study we utilized this model feature to assess the effect of different grain sizes on the estimation of ES indicators and thus to shed light on the level of ES integration in a Central European mountain forest landscape. According to Villa et al. (2014) ES quantification methods must be quantitative and scalable. The ES indicators used in the presented study are transparent and quantitative and allow the analysis of trade-offs among ES. The spatial simulation and assessment approach can be scaled continuously from tree to landscape level.

To isolate the effect of management as such a no-intervention regime (NOM) has also been implemented and used for comparison.

4.1 Landscape level ES provisioning under BAU management

BAU management and the related cutting intensity has lead to increasing volume stocks. From the mean annual increment of 5.7 $m^3ha^{-1}yr^{-1}$ 33% were harvested. Another 10% were lost to bark beetle induced tree mortality which, at mortality rates of 0.58 $m^3ha^{-1}yr^{-1}$, could not be salvaged at reasonable costs and therefore largely remained in the forest. At the end of the simulation period the mean standing stock was over 600m^3ha^{-1} with the clear tendency to increase further. On one hand this increased the in situ carbon pools. On the other, however, it also increases the risk of storm damage (Pasztor et al. 2014a) which may then in turn negatively feed back on the climate change mitigation effect via in situ Carbon storage. Due to the low felling intensity avalanche (API) and landslide protection (LPI) improved over the 100-year simulation period to sufficient levels at almost the entire landscape area. This did not change significantly under climate change conditions. However, the potential for negative climate change impacts has been revealed under climate change scenario c5 and the related increase of bark beetle damage of more than 500% under the NOM regime. It should be noted that in the current study the avalanche protection index did not include gap formation by disturbances or management in explicit form (compare Maroschek et al. 2014) and may therefore overestimate the protection effect. However, at a grain size of 1ha the employed indicators for protective effects can be considered as suitable for the detection of protection deficiencies.

In the long run, increasing the shares of broadleaves and conifers which are less vulnerable under warmer climates is a useful means to increase the resistance against disturbance agents. Detrimental to this adaptive management strategy was the high browsing pressure in the area which actually renders any significant shift in species composition as highly unrealistic. The bird habitat quality in initial phases of the analysis period is insufficient on about 1/3 of the landscape. However, it must be noted that this is mostly due to missing large snags which could not be realistically initialized from available information. From period P2 onward simulation results indicated that simulated tree mortality generates realistic numbers of snags in the forest.

4.3 Spatial heterogeneity and multifunctionality

Our analysis showed that mean estimates of ES indicators for an entire landscape may just partly depend on grain size of such an assessment. However, the spatial variability of ES indicators may differ substantially, depending on grain size. As a general pattern, analysis revealed the largest variation for 1ha, smallest for 10ha grain size, and a decrease in spatial variation over time for most ES indicators, independent of grain size. The fine-grained cutting pattern of BAU management homogenized most ES indicators in course of period P2 and P3, after an initial increase in spatial variation. In the NOM regime this homogenizing effect is less visible. Of course these results cannot be generally extrapolated to any other landscape because they largely depend on the interplay of harvesting pattern and major ecosystem processes (growth, regeneration, mortality). However, such studies are rarely reported in the literature (compare Gret-Regamey et al. 2014) but can shed light on the importance of spatial scale in ES assessments.

The set of ES considered in the presented study is typical for European mountain forests: timber production, nature and habitat conservation and protection against gravitational hazards. In situ Carbon sequestration may be a general public interest as well. BAU management sacrifices timber harvests in favor of Carbon sequestration and bird habitat provisioning. To which extent the protective services would be affected by intensified harvests is not easy to guess and would require thorough analysis. This trend is even stronger visible from the analysis of the NOM regime which, in general, shows in throughout the entire analysis periods better performance in all non-timber ES. However, what must be noted is that the share of admixed species is further reduced in NOM and that the mean tree age is increasing without initialization of regeneration. Thus, in the long run NOM may enter a phase of reduced ES provisioning and lower resilience compared to BAU.

That the non-timber ES in our analysis are neutral or even complementary over long time is shown by the multifunctional share in landscape area. Also Boncina (2011) discussed approaches to integrate nature conservation values in forest management. The reduction in multifunctional area when the number of demanded ES is increased from two to four is surprisingly low (from about 80% to 60% under BAU). NOM has in general higher multifunctional area shares.

With no explicit benchmarks available it is difficult to qualify BAU management in the study area. Regarding timber production it is obvious that this ES could be intensified. Protective effects against avalanche release, landslides and erosion appear as sufficient for large shares of the landscape. Habitat quality for various protected bird species is already maintained by current management at vast shares of the analyzed forest. Summarizing, the overall remaining question is whether it is possible to intensify timber harvests without jeopardizing the other demanded ES and in preparing the forest for conditions of climatic changes. Whether such a management approach can be identified will be the focus of further work.

Acknowledgements

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References

Boncina A (2011) Conceptual approaches to integrate nature conservation into forest management: a central European perspective. Int For Rev 13:13-22.

Bußjager P (2007) ‘‘… zu Luxusbauten wird kein Holz verabfolgt!’’- Die Geschichte des Forstfonds des Standes Montafon. In: Malin H, Maier B, Donz-Breuß M (eds) Montafoner Standeswald—Montafoner Schriftenr. 18. Heimatschutzverein Montafon, Schruns, pp 9–24.

Côté P, Tittler R, Messier C, Kneeshaw DD, Fall A, Fortin MJ (2010) Comparing different forest zoning options for landscape-scale management of the boreal forest: Possible benefits of the TRIAD. For.Ecol.Manage. 259(3): 418–427.

Didion M, Kupferschmid AD, Lexer MJ, Rammer W, Seidl R, Bugmann H (2009) Potentials and limitations of using large-scale forest inventory data for evaluating forest succession models. Ecological Modelling, 220(2):133-147.

Dorren LKA, Berger F, Imeson AC, Maier B, Rey F (2004) Integrity, stability and management of protection forests in the European Alps. For Ecol Manag. 195:165–176.

European Environment Agency (2010) Europe's ecological backbone: recognising the true value of our mountains. EEA Report No 6/2010

Frehner M, Wasser B, Schwitter R (2005) Nachhaltigkeit und Erfolgskontrolle im Schutzwald. Wegleitung für Pflegemassnahmen in Wäldern mit Schutzfunktion, Bundesamt für Umwelt, Wald und Landschaft, Bern

Fries C, Carlsson M, Dahlin B et al (1998) A review of conceptual landscape planning models for multiobjective forestry in Sweden. Can J For Res 28:159–167

Grabherr G (2000) Biodiversity in mountain forests. In: Price M, Butt N, Forests in sustainable mountain development, IUFRO Series no 5.

Gret-Regamey A, Weibel B, Bagstad KJ, Ferrari M, Geneletti D, Klug H, Schirpke U, Tappeiner U (2014) On the effects of scale for ecosystem services mapping. PLOS ONE DOI:10.1371/journal.pone.0112601

Hewitt CD, Griggs DJ (2004) Ensembles-Based Predictions of Climate Changes and Their Impacts (ENSEMBLES), Eos Trans. AGU, 85(52), 566, doi: 10.1029/2004EO520005.

Hanewinkel M, Cullmann DA, Schelhaas M-J et al (2012) Climate change may cause severe loss in the economic value of European forest land. Nat Clim Chang 3:203–207. doi:10.1038/nclimate1687

Hollaus M, Wagner W, Eberhöfer C, Karel W (2006) Accuracy of large-scale canopy heights derived from LiDAR data under operational constraints in a complex alpine environment. ISPRS J Photogramm Remote Sens 60:323–338. doi:10.1016/j.isprsjprs.2006.05.002

Hollaus M, Wagner W, Maier B, Schadauer K (2007) Airborne laser scanning of forest stem volume in a mountainous environment. Sensors 7:1559–1577. doi:10.3390/s7081559

Huber MO, Eastaugh CS, Gschwantner T , Hasenauer H, Kindermann G, Ledermann T, Lexer MJ, Rammer W, Schörghuber S, Sterba H (2013) Comparing simulations of three conceptually different forest models with National Forest Inventory data. Environmental Modelling & Software, 40:88-97.

Jacobsen BJ, Vedel SE, Thorsen BJ (2013) Assessing costs of multifunctional NATURA 2000 management restrictions in continuous cover beech forest management. Forestry 86:575-582.

Jost L (2007) Partitioning diversity into independent alpha and beta components. Ecology 88:2427–2439.

Kaljonen M, Primmer E, De Blust G, Nijnik M, Kulvik M (2007) Multifunctionality and biodiversity conservation – institutional challenges. In: Chmelievski T. (ed.). Nature Conservation Management: from idea to practical issues. Lublin-Lodz-Helsinki-Aarhus, pp. 53-69.

Lamas T, Eriksson LO (2003) Analysis and planning systems for multiresource, sustainable forestry: the Heureka research programme at SLU. Can J For Res 33:500–508. doi:10.1139/x02-213

Landsberg JJ, Waring RH (1997) A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. For Ecol Manag 95:209–228. doi:10.1016/S0378-1127(97)00026-1

Lexer MJ, Seidl R (2009) Addressing biodiversity in a stakeholder-driven climate change vulnerability assessment of forest management. For Ecol Manag 258:158-167.

Lindner M, Maroschek M, Netherer S et al (2010) Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. For Ecol Manag 259:698–709. doi:10.1016/j.foreco.2009.09.023

Malin H, Lerch T (2007) Schutzwaldbewirtschaftung im Montafon. In: Malin, H., Maier, B., Donz-Breuß, M. (eds.) Montafoner Standeswald—Montafoner Schriftenr. 18. Heimatschutzverein Montafon, Schruns, pp 115–128.

Malin H, Maier B (2007) Der Wald—Das grune Ruckgrat des Montafon. In: Malin, H., Maier, B., Donz-Breuß, M. (eds.) Montafoner Standeswald—Montafoner Schriftenr. 18. Heimatschutzverein Montafon, Schruns, pp 91–114

Maroschek M, Rammer W, Lexer MJ (2014) Using a novel assessment framework to evaluate protective functions and timber production in Austrian mountain forests under climate change. Reg Environ Change, DOI 10.1007/s10113-014-0691-z.

Niese G (2011) Österreichs Schutzwälder sind total überaltert. BFW-Praxisinformation, Wien, (24): 29-31.

Nijnik M, Nijnik A, Lundin L, Staszewski T, Postolache C (2015) A study of stakeholder´s perspectives on multifunctional forests in Europe. Forests, Trees and Livelihoods 19(4):341-358.

Pasztor F, Matulla C, Rammer W, Lexer MJ (2014a) Drivers of the bark beetle disturbance regime in Alpine forests in Austria. For Ecol Manag 318:349–358. doi:10.1016/j.foreco.2014.01.044

Pasztor F, Matulla C, Zuvela-Aloise M, Rammer W, Lexer MJ (2014b) Developing predictive models of wind damage in Austrian forests. Annals of Forest Science, DOI: 10.1007/s13595-014-0386-0

Peng C (2000) Understanding the role of forest simulation models in sustainable forest management. Environ. Impact Asses. 20:481-501.

Raudsepp-Hearne C, Peterson GD, Bennett EM (2010) Ecosystem service bundles for analyzing trade-offs in diverse landscapes. PNAS 107:5242-5247.

Roces-Diaz JV, Diaz-Varela RA, Alvarez-Alvarez P, Recondo C, Diaz-Varela ER (2015) A multiscale analysis of ecosystem services supply in the NW Iberian Peninsula from a functional perspective. Ecological Indicators 50:24-34.

Seidl R, Lexer MJ, Jäger D, Hönninger K (2005) Evaluating the accuracy and generality of a hybrid patch model. Tree Physiol 25:939–951

Seidl R, Rammer W, Jäger D (2007) Assessing trade-offs between carbon sequestration and timber production within a framework of multi-purpose forestry in Austria. For Ecol Manag 248:64–79. doi:10.1016/j.foreco.2007.02.035

Seidl R, Rammer W, Jäger D, Lexer MJ (2008) Impact of bark beetle (Ips typographus L.) disturbance on timber production and carbon sequestration in different management strategies under climate change. For Ecol Manag 256:209–220. doi:10.1016/j.foreco.2008.04.002

Seidl R, Rammer W, Lexer MJ (2009) Estimating soil properties and parameters for forest ecosystem simulation based on large scale forest inventories [Schatzung von Bodenmerkmalen und Modellparametern fur die Waldokosystemsimulation auf Basis einer Großrauminventur]. Allg Forst- und Jagdzeitung 180:35–44.

Suda M, Pukall K (2014)Multifunktionale Forstwirtschaft zwischen Inklusion und Extinktion (Essay). Schweiz Z Forstwes 165(11):333-338.

Villa F, Bagstad KJ, Voigt B, Johnson GW, Portela R, Honzak M, Batker D (2014) A methodology for adaptable and robust ecosystem service assessment. PLOS ONE 9(3):1-18.

Woltjer M, Rammer W, Brauner M et al (2008) Coupling a 3D patch model and a rockfall module to assess rockfall protection in mountain forests. J Environ Manag 87:373–388. doi:10.1016/j.jenvman.2007.01.031

Figure Captions

Fig. 1 Study landscape structured into 18 harvesting units as simulation entities and 131 skyline tracks to implement BAU management 2010-2110

Fig. 2 Three grain sizes for the assessment of ES indicators in the study landscape (indicated as black boxes for A: 1ha, n=84; B: 5ha, n=18; C: 10ha, n=15). Dark grey area shows forested area, light grey non-forest area

Fig. 3 Impact of five climate change scenarios on ES indicators under BAU management in period P3 (2078-2110) in relation to current climate (c0)

Fig. 4 Effect of grain size on bird habitat quality (BHQ) and landslide and erosion protection index (LPI) in period P3 (2078-2110) under current climate (c0) and strong warming (c5)

Fig. 5 Coefficient of variation (CV) for selected ES indicators over the three assessment periods P1-P3 in dependence of grain size and three climate scenarios (current climate c0, climate change scenarios c1 and c5)

Fig. 6 Multifunctional share of landscape area (bundles of ES in performance category 2 (moderately good) or 3 (good) in period P3 (2078-2110)) under current climate (c0) and two climate change scenarios (c1, c5) under BAU management and the no-management regime (NOM). Assessment scale: 1ha (white diamond), 5ha (grey circle) and 10ha (black triangle) samples. Symbols represent mean area percentage, whiskers indicate worst and best case within given situation. Considered ES: Carbon storage, bird habitat, protection against avalanches and landslides

Figure1
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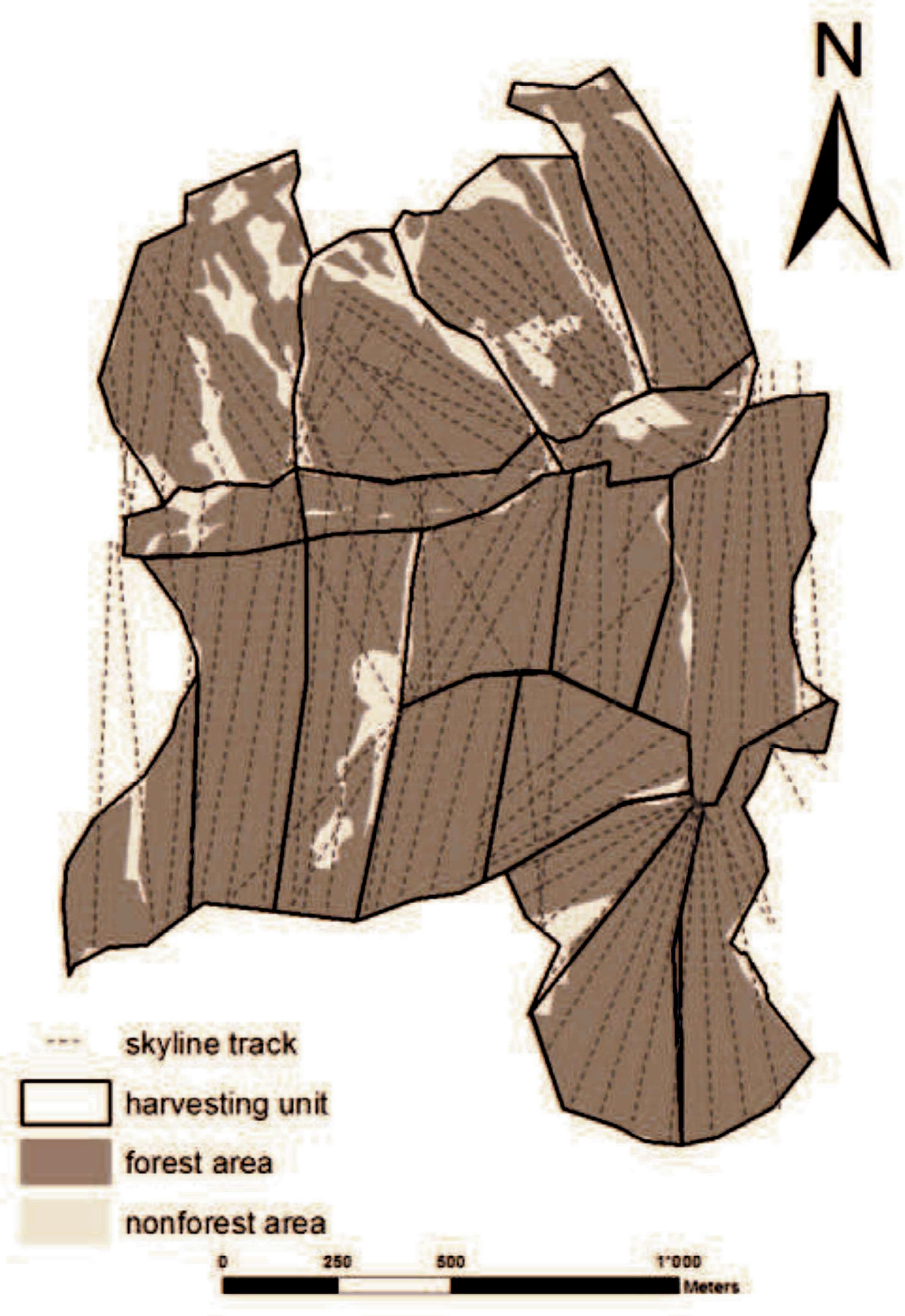
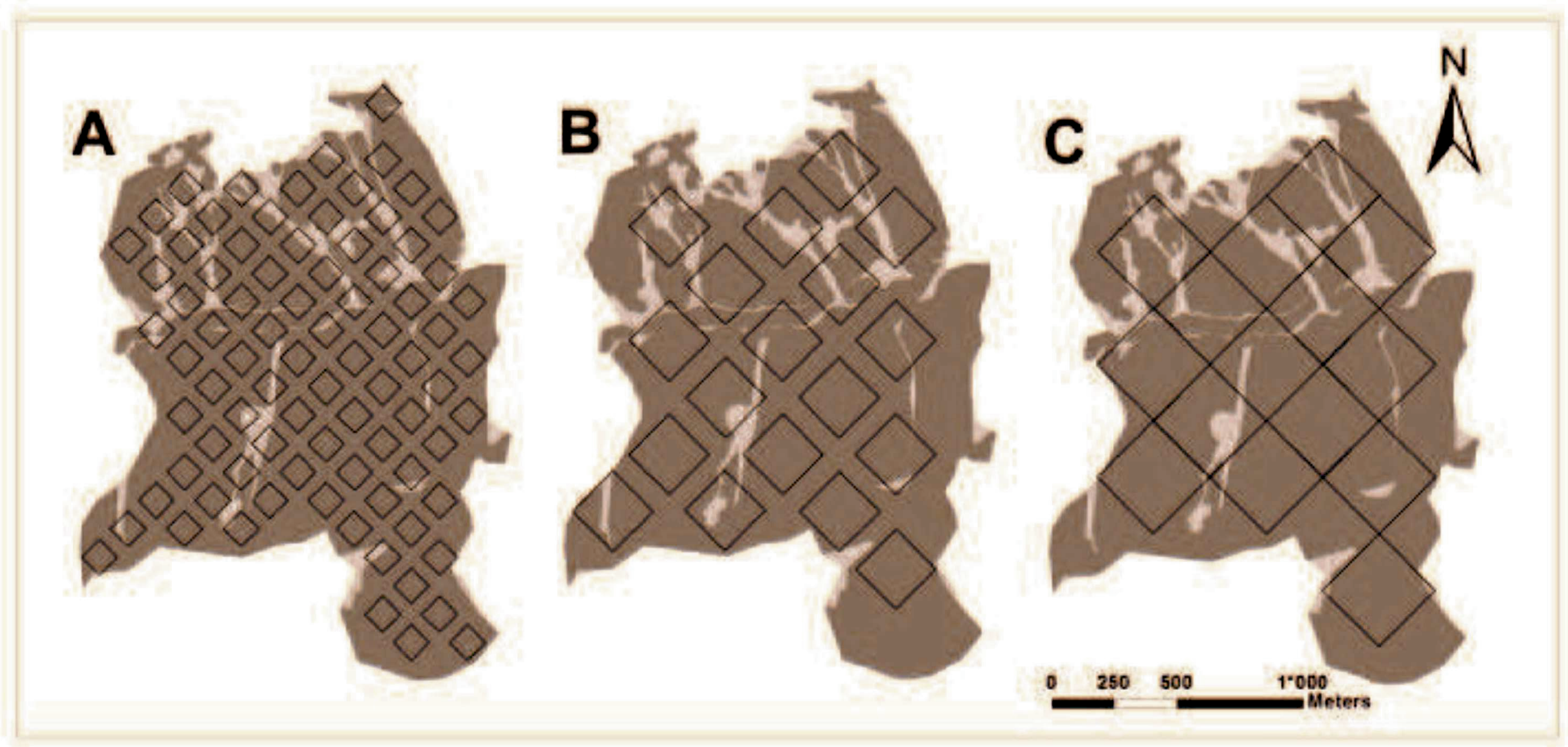


Figure2



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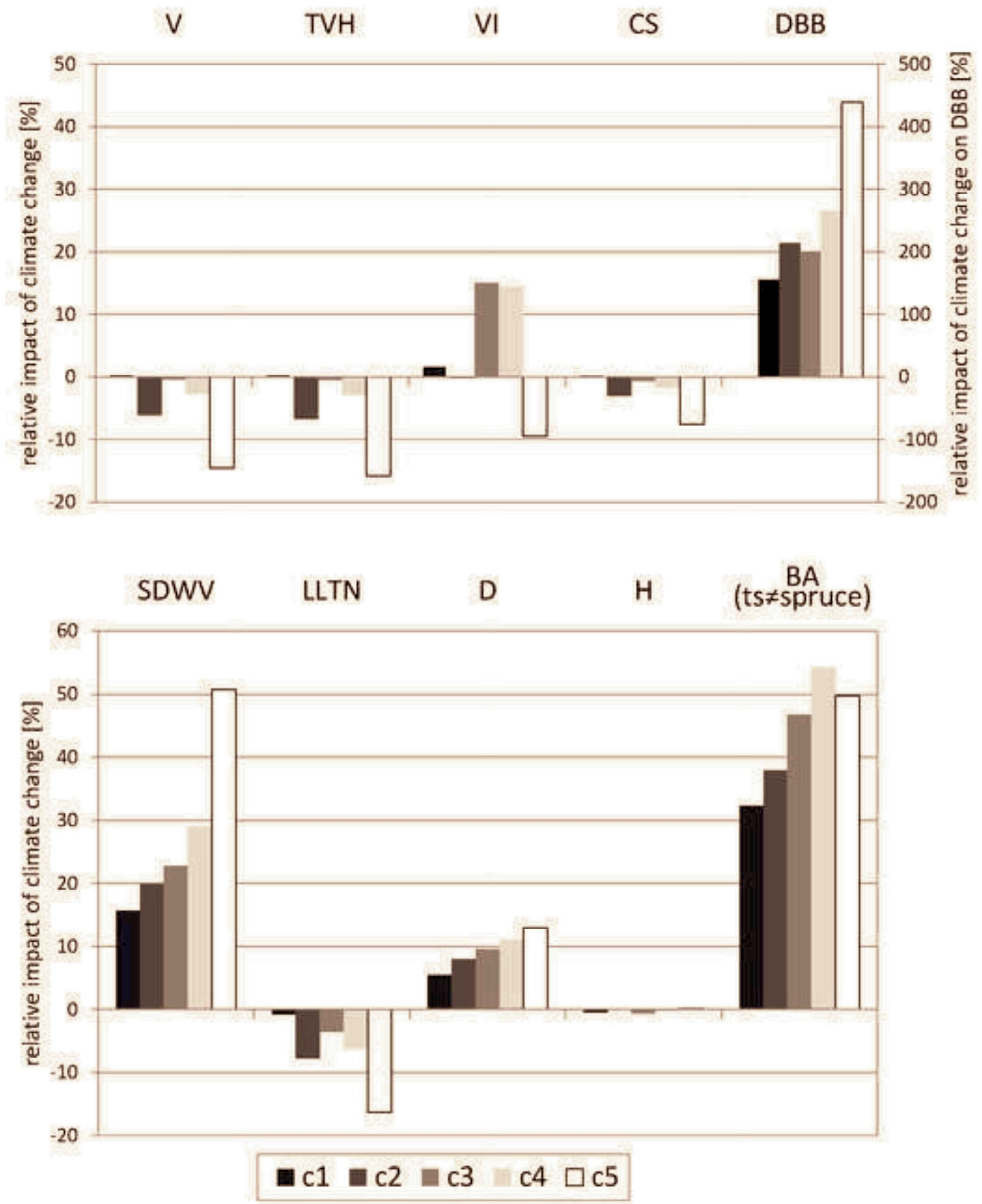

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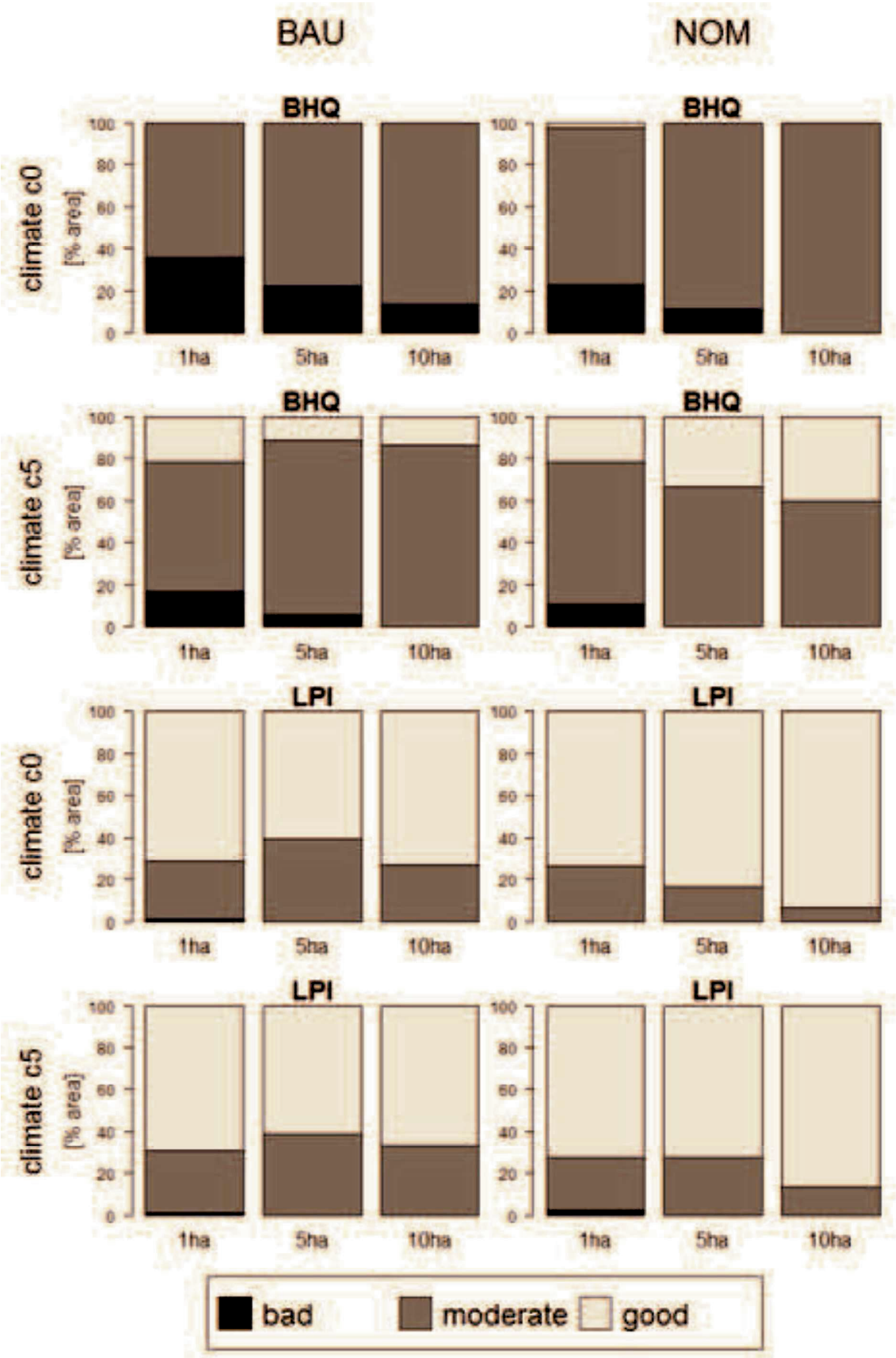

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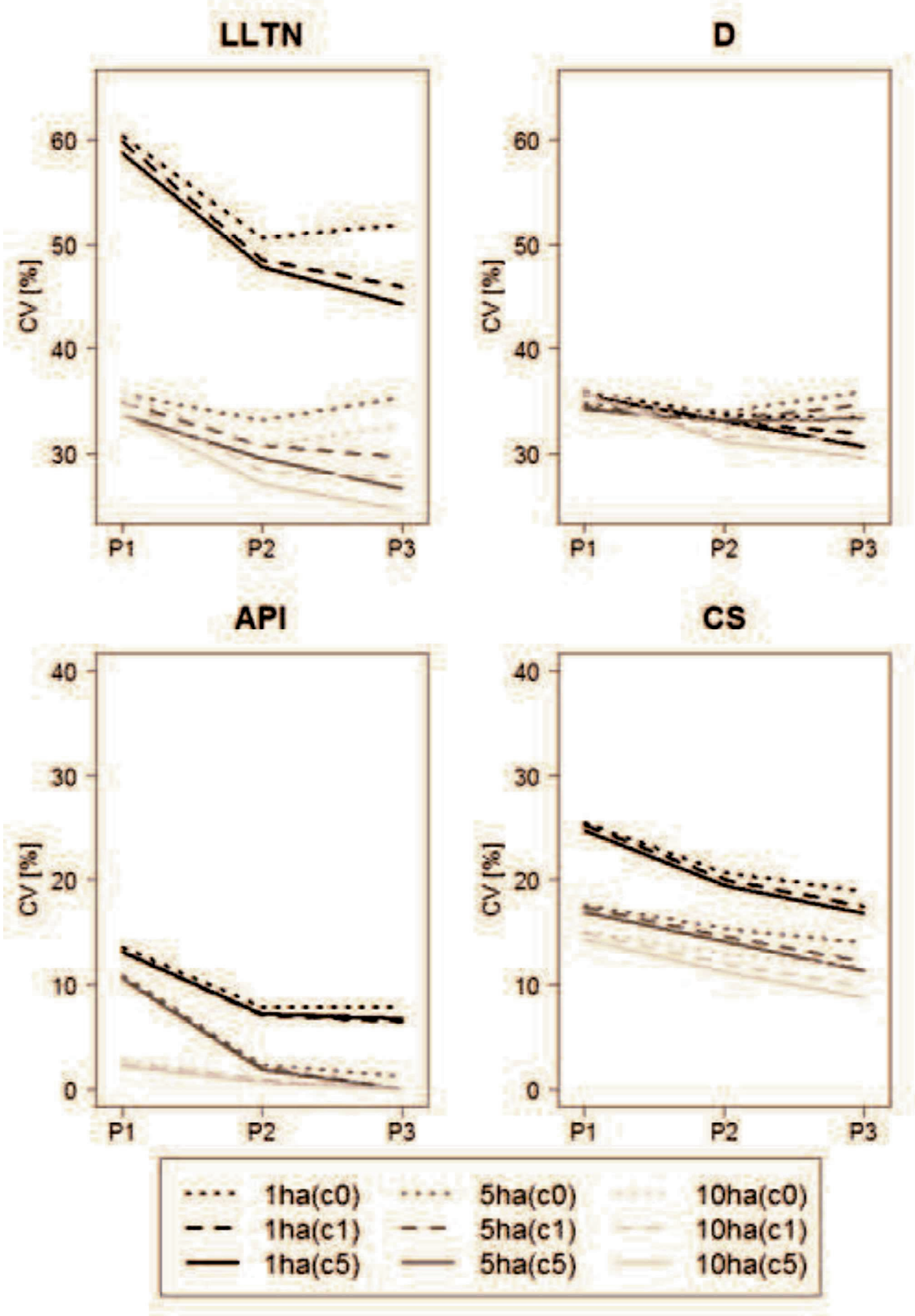

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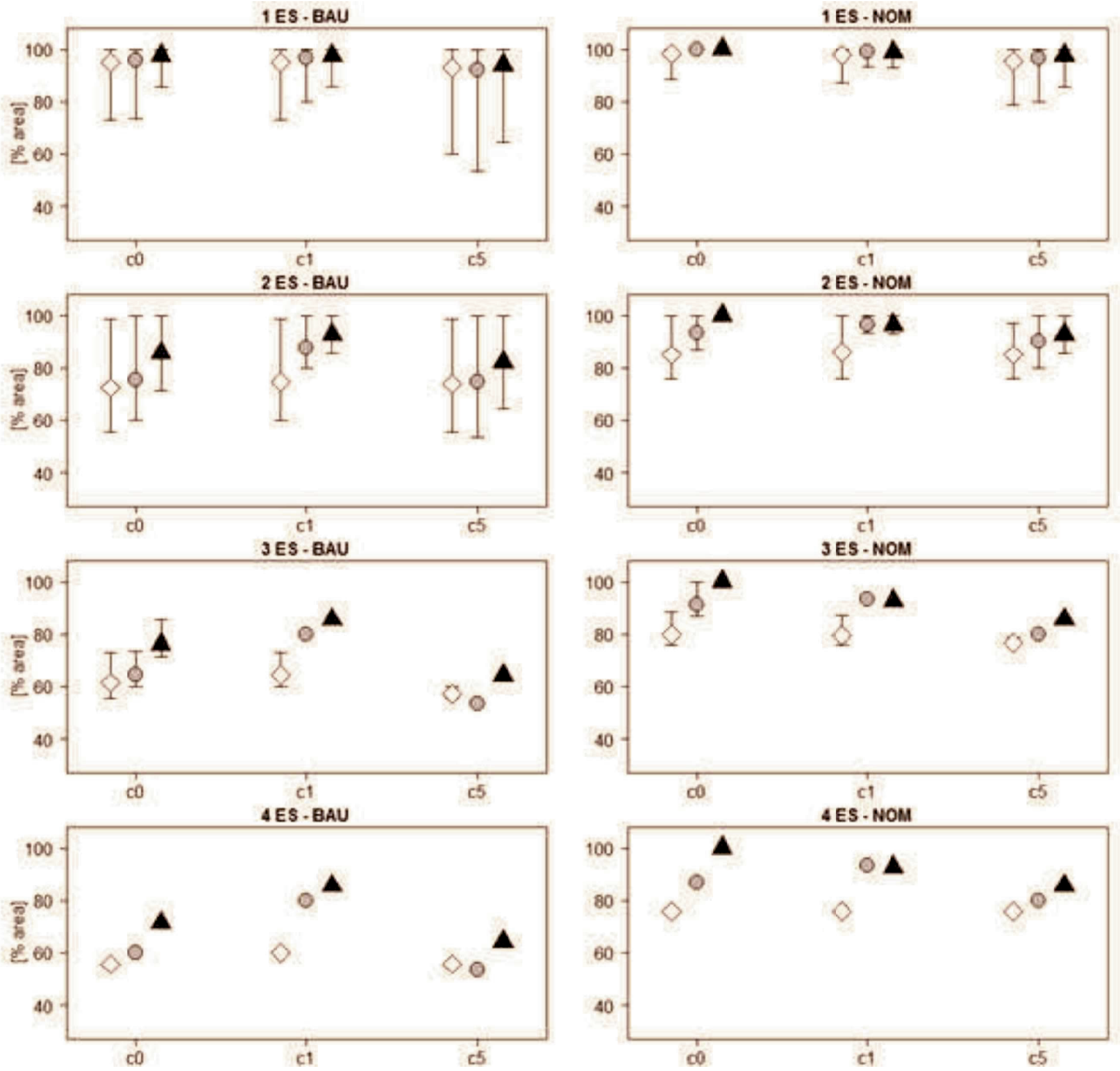
1 ES - BAU
1 ES - NOM
2 ES - BAU
2 ES - NOM
3 ES - BAU
3 ES - NOM
4 ES - BAU
4 ES - NOM
[% area]
100
80
60
40
c0
c1
c5

Table1

Table 1. Ecosystem service indicators for current management (BAU) and the no-management regime (NOM) under current climate (c0) for three assessment periods: P1 = 2010-2043, P2 = 2044-2077, P3 = 2078-2110. Classification categories for BHQ and LPI: 1=bad, 2=moderate, 3=good; provided in area shares of categories 1/2/3. Indicator values for BHQ, API and LPI based on 1ha samples of the landscape, all other indicators based on HU simulation entities.

Acronym	Explanation	unit	P1		P2		P3	
			BAU	NOM	BAU	NOM	BAU	NOM
Timber production								
V	Standing volume	[m^3 ha^{-1}]	436.5	466.4	450.4	525.6	490.1	599.6
THV	Annual volume harvested	[m^3 ha^{-1} yr^{-1}]	1.9	-	1.6	-	2.8	-
VI	Annual net volume increment	[m^3 ha^{-1} yr^{-1}]	4.9	5.0	5.6	5.6	6.5	5.9
BBD	Volume killed by bark beetles	[m^3 ha^{-1} yr^{-1}]	0.6	0.6	0.6	0.6	0.5	0.5
Carbon sequestration								
CS	Carbon contained in biomass (trees, standing deadwood, coarse woody debris and soil carbon)	[t ha^{-1}]	220.2	237.6	218.2	244.4	222.9	253.1
Biodiversity								
D	Diversity of tree species (true diversity (Jost, 2006) by basal area)	[-]	1.48	1.49	1.39	1.42	1.30	1.33
H	Tree size diversity (mean Shannon diversity of DBH and height)	[-]	2.36	2.36	2.38	2.35	2.41	2.34
AA	Basal area share of Abies alba	[%]	6.2	6.1	4.6	4.6	3.4	3.6
BL	Basal area share of broadleaves	[%]	3.4	3.3	3.3	2.9	2.6	2.0
SDWV	Standing deadwood volume	[m^3 ha^{-1}]	22.9	24.4	20.5	23.5	23.8	28.8
LLTN	Large living trees (DBH >50cm)	[n ha^{-1}]	56.1	60.4	54.5	65.0	49.7	66.3
BHQ	Bird habitat quality	[%]	0.51/0.39/0.10	0.46/0.44/0.10	0.40/0.58/0.01	0.36/0.60/0.05	0.36/0.64/0.00	0.23/0.75/0.02
Protection against gravitational hazards								
API	Avalanche protection index	[0-1]	0.91	0.93	0.96	0.98	0.98	0.98
LPI	Landslide and erosion protection	[%]	0.07/0.45/0.48	0.04/0.42/0.55	0.02/0.26/0.71	0.00/0.25/0.75	0.01/0.27/0.71	0.00/0.26/0.74

Table2

Table 2. ES indicators based on different grain size (1ha, 5ha, 10ha) for BAU management and the NOM regime under current climate (c0) in three assessment periods (mean and standard deviation). P1 = 2010-2043, P2 = 2044-2077, P3 = 2078-2110. Classification categories for BHQ and LPI: 1=bad, 2=moderate, 3=good; provided in area shares of categories 1/2/3. Grey shade and letters denote significant differences between periods.

Indicator	grain size	BAU			NOM		
		P1	P2	P3	P1	P2	P3
V	1ha	366.9 ±162.2	377.3 ±124.9	406.1 ±118.9	395.7 ±174.1[b]	442.5±150.0[b]	500.3 ±142.3[a]
	5ha	361.9 ±101.2	359.9 ±84.8	386.4 ±80.1	383.9 ±103.7[b]	419.7±95.8[ab]	471.5 ±86.2[a]
	10ha	367.9 ±82.6	372.8 ±60.8	398.6 ±58.8	391.7 ±88.7[b]	434.9±71.5[ab]	490.4 ±58.7[a]
CS	1ha	224.4 ±54.8	222.5 ±39.6	226.6 ±35.0	244.0 ±60.4	250.1±48.9	259.3 ±43.7
	5ha	225.7 ±35.4	221.2 ±29.2	225.8 ±27.4	240.8 ±40.6	244.0±34.4	252.2 ±28.7
	10ha	225.5 ±28.0	223.1 ±22.6	227.1 ±22.5	240.9 ±34.7	246.8±27.8	255.7 ±22.5
D	1ha	1.38 ±0.50	1.36 ±0.48	1.26 ±0.39	1.37 ±0.49	1.32±0.44	1.25 ±0.38
	5ha	1.42 ±0.49	1.41 ±0.47	1.32 ±0.47	1.42 ±0.49	1.38±0.46	1.30 ±0.43
	10ha	1.52 ±0.54	1.49 ±0.46	1.37 ±0.41	1.51 ±0.54	1.45±0.45	1.35 ±0.40
SDWV	1ha	22.8 ±17.7	21.4 ±8.4	24.6 ±7.3	24.1 ±17.8[b]	24.3±9.2[b]	29.5 ±8.5[a]
	5ha	22.3 ±9.3	20.3 ±4.7	23.5 ±4.4	23.5 ±9.8	23.4±5.5	28.6 ±4.8
	10ha	21.9 ±8.1	20.9 ±3.2	24.1 ±2.9	23.1 ±8.6[b]	23.8±3.8[ab]	28.8 ±3.6[a]
LLTN	1ha	54.4 ±31.9	53.2 ±25.5	48.2 ±21.9	59.4 ±34.8	63.8±30.5	64.9 ±28.8
	5ha	55.6 ±18.9	52.1 ±15.8	46.3 ±13.3	59.3 ±20.0	61.6±18.2	61.4 ±16.4
	10ha	55.4 ±18.3	53.0 ±14.4	46.6 ±12.6	59.3 ±20.0	62.8±17.0	62.2 ±15.4
BHQ	1ha	[0.51/0.39/0.10]	[0.40/0.58/0.01]	[0.36/0.64/0.00]	[0.46/0.44/0.10][c]	[0.36/0.60/0.05][cb]	[0.23/0.75/0.02][a]
	5ha	[0.22/0.72/0.06]	[0.28/0.72/0.00]	[0.22/0.78/0.00]	[0.17/0.67/0.17]	[0.11/0.89/0.00]	[0.11/0.89/0.00]
	10ha	[0.40/0.53/0.07]	[0.27/0.73/0.00]	[0.13/0.87/0.00]	[0.20/0.67/0.13]	[0.13/0.87/0.00]	[0.00/1.00/0.00]
API	1ha	0.91 ±0.14[b]	0.96 ±0.09[a]	0.98 ±0.06[a]	0.93 ±0.12[b]	0.98 ±0.07[a]	0.98 ±0.07[a]
	5ha	0.94 ±0.11	0.98 ±0.04	1.00 ±0.00	0.96 ±0.10	0.99 ±0.02	1.00 ±0.00
	10ha	0.99 ±0.03	0.99 ±0.02	1.00 ±0.00	0.99 ±0.02	1.00 ±0.01	1.00 ±0.00
LPI	1ha	[0.07/0.45/0.48][b]	[0.02/0.26/0.71][a]	[0.01/0.27/0.71][a]	[0.04/0.42/0.55][b]	[0.00/0.25/0.75][a]	[0.00/0.26/0.74][a]
	5ha	[0.00/0.67/0.33][a]	[0.00/0.39/0.61][a]	[0.00/0.39/0.61][a]	[0.00/0.50/0.50][ab]	[0.00/0.11/0.89][a]	[0.00/0.17/0.83][ab]
	10ha	[0.00/0.60/0.40][a]	[0.00/0.33/0.67][a]	[0.00/0.27/0.73][a]	[0.00/0.47/0.53][a]	[0.00/0.13/0.87][a]	[0.00/0.07/0.93][a]

Table3

Table 3. Effect of climate change scenarios c0, c1 and c5 on ES indicators for different grain sizes in BAU management and NOM regime in period P3 (2078-2110). Classification categories for BHQ and LPI: 1=bad, 2=moderate, 3=good; provided in area shares of categories 1/2/3. Grey shade and letters denote significant differences between climate scenarios.

Indicator	grain size	BAU			NOM		
		c0	c1	c5	c0	c1	c5
V	1ha	406.1[a]	411.4[b]	345.7[b]	500.3[a]	508.1[a]	434.0[b]
	5ha	386.4[a]	387.6[a]	319.7[b]	471.5[ab]	476.3[a]	397.6[b]
	10ha	398.6[a]	398.7[a]	331.9[b]	490.4[a]	493.2[a]	415.7[b]
CS	1ha	226.6[a]	228.2[a]	212.4[b]	259.3[ab]	261.2[a]	243.4[b]
	5ha	225.8	226.5	210.0	252.2	253.5	234.6
	10ha	227.1	227.7	212.1	255.7	256.7	238.6
D	1ha	1.26	1.34	1.40	1.25	1.31	1.37
	5ha	1.32	1.42	1.50	1.30	1.37	1.46
	10ha	1.37	1.47	1.57	1.35	1.43	1.53
SDWV	1ha	24.6[a]	28.1[b]	36.0[a]	29.5[b]	32.8[b]	42.8[a]
	5ha	23.5[b]	27.2[b]	35.1[a]	28.2[b]	31.4[b]	42.1[a]
	10ha	24.1[b]	27.8[b]	35.6[a]	28.8[b]	32.5[b]	42.2[a]
LLTN	1ha	48.2[a]	47.7[ab]	40.2[b]	64.9	65.0	55.5
	5ha	46.3	45.2	37.3	61.4	60.8	50.8
	10ha	46.6	45.4	38.2	62.2	61.5	52.0
BHQ	1ha	[0.36/0.64/0.00][b]	[0.32/0.63/0.05][b]	[0.17/0.62/0.21][a]	[0.23/0.75/0.02][c]	[0.19/0.69/0.12][b]	[0.11/0.68/0.21][a]
	5ha	[0.22/0.78/0.00][a]	[0.06/0.94/0.00][a]	[0.06/0.83/0.11][a]	[0.11/0.89/0.00][b]	[0.00/0.89/0.11][b]	[0.00/0.67/0.33][a]
	10ha	[0.13/0.87/0.00][a]	[0.00/1.00/0.00][a]	[0.00/0.87/0.13][a]	[0.00/1.00/0.00][b]	[0.00/0.93/0.07][b]	[0.00/0.60/0.40][a]
API	1ha	0.98	0.98	0.97	0.98	0.98	0.98
	5ha	1.00	1.00	0.99	1.00	1.00	1.00
	10ha	1.00	1.00	1.00	1.00	1.00	1.00
LPI	1ha	[0.01/0.27/0.71]	[0.01/0.26/0.73]	[0.01/0.30/0.69]	[0.00/0.26/0.74]	[0.00/0.25/0.75]	[0.02/0.25/0.73]
	5ha	[0.00/0.39/0.61]	[0.00/0.28/0.72]	[0.00/0.39/0.61]	[0.00/0.17/0.83]	[0.00/0.11/0.89]	[0.00/0.28/0.72]
	10ha	[0.00/0.27/0.73]	[0.00/0.27/0.73]	[0.00/0.33/0.67]	[0.00/0.07/0.93][a]	[0.00/0.07/0.93][a]	[0.00/0.13/0.87][a]