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Multifunctionality in European mountain forests – An optimization under changing climatic conditions

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Fabian H. Härtl*, Ivan Barka, W. Andreas Hahn, Tomáš Hlásny, Florian Irauschek, Thomas Knoke, Manfred J. Lexer, Verena C. Griess*

*The authors contributed equally to the manuscript

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Author(s)	Fabian H. Härtl, Ivan Barka, W. Andreas Hahn, Tomáš Hlásny, Florian Irauschek, Thomas Knoke, Manfred J. Lexer, Verena C. Griess
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Abstract:

Maintaining multifunctionality of forests is a crucial task with a changing climate and increasing demands from society. We combined forest growth simulations with a risk-integrating economic optimization tool to derive management plans for different climate scenarios, to investigate the impact of climatic change on forest management, and then interdependencies between different forest services, as well as to provide economic information regarding the costs for providing certain services at the enterprise level. To do so, long-term growth projections for various tree species are coupled with different management scenarios.

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1 Introduction

Twenty-nine percent of the European Union's (EU27) land surface is covered by mountains (EEA 2010), and forests cover 41% of this mountainous area, where they provide an outstanding number of ecosystem services (ES). Mountain ecosystems can only continue to provide all these services if they are considered in forest management planning both at local, landscape and regional scales. A general framework aiming at securing multiple services provided by forest ecosystems in the context of sustainable forest management (SFM) was defined by the Ministerial Conference for the Protection of Forests in Europe in 2003. However, this promising concept has yet to be made operational at regional and local scales. Even though during the last decades knowledge about the numerous ecological, societal and climatological services forest ecosystems provide has greatly increased, it remains a fact that in the majority of the cases only their ability to produce timber is being considered in their economic estimation. Other ES like carbon storage provided by forests are rarely ever taken into consideration (e.g. in Bjørnstad und Skonhoft 2002; Pihlainen et al. 2014, for an overview see Niinimäki et al. 2013), often because of the problem of non-existent markets and prices (Knoke et al. 2008).

With a changing climate and increasing demands regarding the services forests have to offer, it becomes clear that maintaining certain services may lead to a decrease in the quantity or quality of other services available from the same source (Seidl et al. 2011). Examples are timber production with a simultaneous provision of habitat requirements, water retention, carbon sequestration and others (Maroschek et al. 2009).

Harvesting intensity as well as spatial allocation and timing of management activities are important drivers for the support of forest multi-functionality. However, optimizing these factors is often carried out based on long term experience. An approach that leads to outcomes that are hardly predictable, especially under a changing climate.

There are numerous publications addressing these issues in a qualitative way (Lindner et al. 2010; Kolström et al. 2011; O'Hara und Ramage 2013; Rist et al. 2013; Grunewald und Bastian 2015) but there is a lack of management strategies derived from those studies using economic models that are capable of involving aspects of risk and to investigate flows and trade-offs between ecosystem services: "*For too long, scientists and managers have tended to view the world as either protected because of the intrinsic or aesthetic value of the area, or developed for its utilitarian benefits. The reality, of course, is that our planet is a mosaic of systems providing people with different bundles of ecosystem services and disservices. We cannot manage these systems effectively if we do not actively seek to measure the flows of these services, examine who is benefiting from them, and consider a range of policies, incentives, technologies and regulations that could encourage better management and sharing of the benefits.*" (Reid et al. 2006)

Accordingly, the leading research objective for this paper is to analyze the effects of economically optimized harvest schedules on the provision of ES and how they will be influenced by climate change.

To take a step towards understanding the interdependencies in this field, as well as to provide information regarding the costs related with the provision of certain services, the advanced optimization tool YAFO (Härtl et al. 2013) was applied to datasets from the two case study areas (CSA) Montafon (Austria) and Goat Backs Mountains (Western Carpathians, Slovakia), which are addressed in the EU funded project ARANGE.

Based on the portfolio theory (Markowitz 1952, 2010) we will determine optimal SFM strategies at stand level. Optimized spatially explicit treatment schedules (distribution of harvests over space and time, determining the optimal timing for harvesting operations) are identified with a non-linear programming approach which integrates risks such as storms and insect outbreaks and a risk-averting perspective in the optimization (Härtl et al. 2013; Härtl 2015).

To do so, long-term and climate-sensitive growth projections for various tree species (and combinations) are coupled with timber price scenarios (bootstrapped from historical time series to retain the correlation structures), natural disturbances (binomially distributed damages) and harvesting cost scenarios. Frequency distributions of financial indicators are generated. Moreover, the provision of ES, such as protection against natural hazards, is estimated under various treatments simultaneously to the financial valuation, and integrated in the optimization. Different treatment portfolios are derived following various combinations of objectives and constraints to compose a virtual long-term forest composition providing specific bundles of ES.

2 Material & Methods

For both selected CSA Austria and Slovakia growth and yield information compatible with YAFO was simulated. The four management scenarios for which growth and yield data was simulated were selected based on data needs for the YAFO optimization as well as panel discussions involving representatives of the CSA and the project partners carrying out simulation and optimization. All management scenarios (see Figure 1) were simulated under a baseline climate scenario representing historic climate conditions of the period 1961-1990 and 5 transient climate change scenarios based on the ENSEMBLES project (see section 2.5.1). The simulation results of the climate change scenarios were averaged, leading to a total of 8 datasets for each CSA (Figure 1). New trees established on harvested areas under scenario “business as usual” (compare Figure 1) are simulated in so called “ingrowth tables”. These “ingrowth” units are simulated as well under current climate and under climate change conditions. Climate change was represented by the mean anomalies in temperature and precipitation over the 5 transient climate change scenarios from the period 2080-2100.

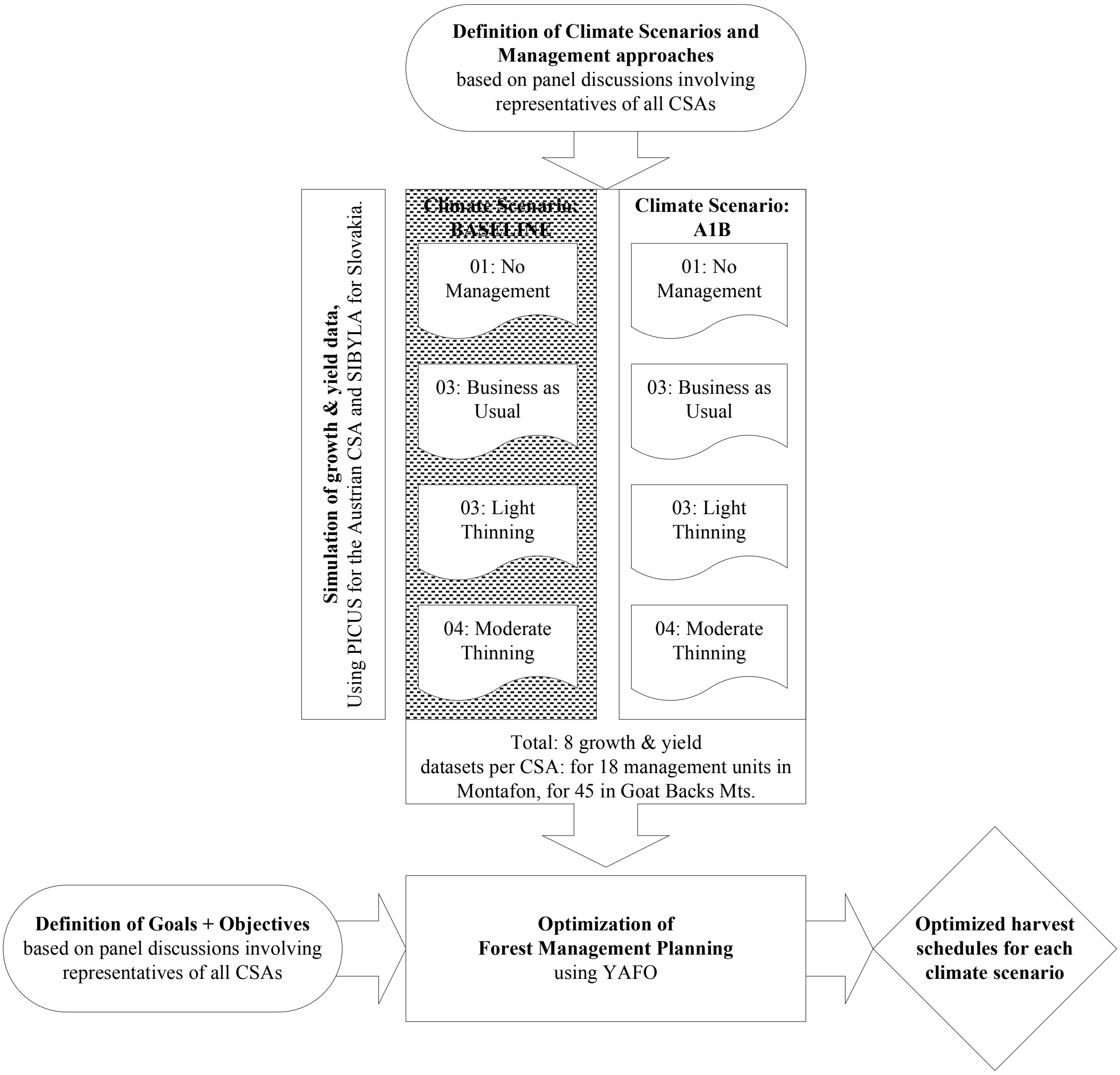

Figure 1: Data flow and description of the overall modelling + optimization approach

2.1 The Optimization Approach

To derive optimized planning schedules we use the risk-sensitive planning support tool YAFO (Härtl et al. 2013) based on non-linear solution techniques. YAFO is programmed using the modeling system AIMMS (Paragon Decision Technology B.V. 2011). In the development version that could be used for this project the number of stands that can be incorporated into the model is unlimited; the same applies to the number of different treatments (or grading scenarios). The maximum forecasting horizon is 20 periods. For this study we chose a period length of 5 years.

YAFO provides three optimization algorithms: a net present value (NPV) optimization without considering any risk factors, a value at risk (VaR) maximisation and a risk utility optimization. The core of the model is a four-dimensional area control scheme of the optimization task that is solved by calculating the optimal assignment of the stand areas (the variables) to the expected revenues (the coefficients). So, in the risk-free case, the objective function has the following form:

$$\max_f Z = \sum_{i,t,u,s} \left(n_{itus} a_{itus}^{n} + k_{its} a_{its}^{k} + n_{itus}^{y} a_{itus}^{ny} + k_{its}^{y} a_{its}^{ky} \right) \cdot (1+r)^{-t}$$

with

$$n_{itus}^{(y)} \coloneqq p_{itus}^{(y)} - c_{itus}^{(y)} - f_{itus}^{(y)}$$

$$k_{its}^{(y)} \coloneqq p_{its}^{k(y)} - c_{its}^{k(y)} - f_{its}^{k(y)}$$

and the constraints:

$$\sum_{s} a_{it'1s}^{n} + \sum_{t=0}^{t'} \sum_{s} \left(a_{it0s}^{n} + a_{its}^{k} \right) = a_i \quad \forall i, t'$$

$$\sum_{s} a_{its}^{k} = a_{it}^{k} \quad \forall i, t$$

$$a_{itus}^{(n,k,y)} \geq 0 \quad \forall i, t, u, s$$

$$\sum_{u} a_{it'u}^{ny} = \sum_{t=0}^{t'} \sum_{s} \left(a_{it0s}^{n} + a_{its}^{k} - a_{it0s}^{ny} - a_{its}^{ky} \right) \quad \forall i, t'$$

Where r = interest rate, t = time, i = stand number, s = grading or treatment option, a_i = area of stand i, n_{itus} = revenues per area in stand i at time t (using harvest option u and grading option s defined as proceeds p_{itus} minus harvesting costs c_{itus} minus cultural costs f_{itus}), k_{its} = revenues per area from salvage felling (proceeds p_{its}^{k} minus harvesting costs c_{its}^{k} minus cultural costs f_{its}^{k}), a_{itus} = thinning area when u=1 and felling area when u=0, a_{its}^{k} = area of salvage felling. For the interest a rate of 1.5% was chosen to reflect the internal rate that can be achieved in Central European forests (Möhring und Rüping 2008). We assume like them that for most forest owners feasible investment alternatives are typically within the forest sector.

The high index y labels variables and parameters of the ingrowth that are of the same structure like those mentioned already. Constraint 1 assures that for every point in time, t', the sum of the area felled (harvest option u = 0 plus salvage areas a^k) to date plus the current area to be thinned (harvest option u = 1) is equal to the stand area a_i. This means that every area not yet felled is automatically thinned. Constraint 2 ensures that the salvage felling area in each period cannot be used as a thinning or final felling option. Constraint 3 prohibits non-negativity regarding the areas assigned to the various treatments. Constraint 4 assures that the model establishes ingrowth areas on any area harvested by regular or salvage logging.

Risks caused by natural hazards like for example storms or bark-beetle as well as timber price fluctuation are considered using the Monte Carlo module of YAFO. A Monte Carlo simulation is a widely applied computational technique to produce distributions of parameters by using randomly generated numbers (Waller et al. 2003; Knoke und Wurm 2006). The advantage of this method is that there can be easily combined different sources of variation – for example ecological and economic influences like in our case.

Now, the objective function Z must be described by its distribution function F_Z. The VaR that has to be maximised is then defined by the p-quantile of the inverse function of F_Z. So under the influence of risk the objective is defined as follows:

$$\max_{f} Z = F_Z^{-1}(p)$$

As F_Z is considered to be approximately Gaussian distributed, the function can be defined by its expected value $E(Z)$ and its variance s_Z^2. Both values are estimated based on the results of the Monte Carlo simulation (MCS). s_Z^2 is the sum over all (co)variances of each possible combination of two forest stands x and y. As (co)variances are calculated by multiplying correlation coefficient with standard deviation as expected value times variation coefficient, we can write:

$$s_Z^2 = \sum_{t,s} \mathbf{e}_{ts}^{\mathrm{T}} \mathbf{C}_{ts} \mathbf{K}_{ts} \mathbf{C}_{ts} \mathbf{e}_{ts}$$

$\mathbf{K}_{ts}$ is a matrix containing the correlation of the possible returns for stand x and y at time t and for grading/treatment option s. $\mathbf{C}_{ts}$ is a diagonal matrix containing the variation coefficients for each stand in its main diagonal. The two matrices are derived by the results of a MCS. The MCS can use either fixed hazard rates or age dependent Weibull functions to incorporate the occurance of salvage loggings. In the Austrian CSA a hazard rate of 3% is used as for the uneven aged stands it is impossible to derive an age dependent hazard rate based on Weibull functions. The latter one are applied in the Slovakian CSA. $\mathbf{e}_{ts}$ = is a vector of the expected net present values for each stand as a function of the area assignment chosen by the optimizer.

YAFO requires a list of the individual stand area sizes, the timber volume per hectare, the harvest revenues, as well as costs per hectare as input data. Additional information that can be provided are initial stand age, volume expansion factors (e.g. to calculate brushwood amounts), and grading data. Each entry in the data list must be identified by stand number, simulation period, a 0/1 value determining if the given information is harvest or remaining volume data, and a scenario number.

The following settings can be changed within the optimization software: number of periods to investigate, period length, interest rate, value at risk threshold, constraints on enterprise level (maximum and minimum felling areas as well as volumes), the parameters of the survival functions for simulating natural hazards, the re-stocking costs per hectare and natural and financial data of the ingrowth development.

After solving the optimization problems, YAFO provides biophysical data on volume development (remaining and harvested timber amounts), split up into final fellings, thinnings, salvage and brushwood amounts, and the development of the ingrowth volumes. If grading information was given the development of each single timber assortment is shown as well. The same is done for the area development. All the data is displayed for the enterprise level as well as for every single stand in each simulation period. By default, carbon sequestration is calculated. So the final output are data sets similar to those used in classic forest inventory and planning (printed books of stand (planning) data or management plans at enterprise level), but adds further details on economical (revenues, net present value) and ecological (carbon balance) estimators.

2.2 Case Study Area: Montafon, Austria

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 1,060 m and 1,800 m a.s.l. (see Figure 2). 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 for more than 500 years (Bußjaeger 2007). The management objectives of the SMF are income generation from timber production, and 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

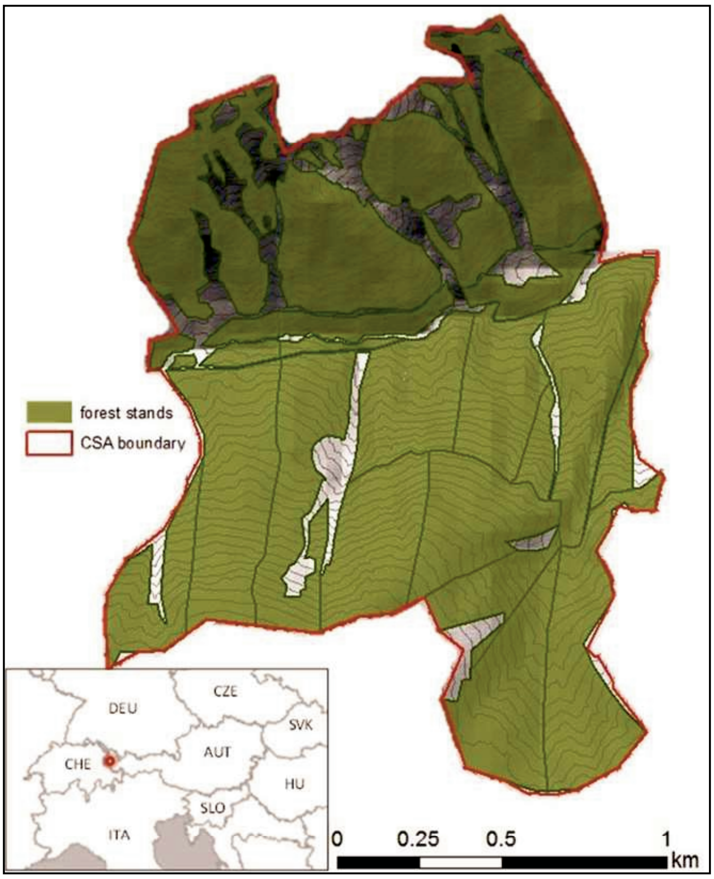

Figure 2: Position of the Case study area Rellstal in Central Europe and map of forest stands including contour lines of 20m.

2.3 Case Study Area: Goat Backs Mountains, Slovakia.

The Goat Back Mts. are located in the Northeast Slovakia (see Figure 3) in the mountain range of the Central Western Carpathians. It covers an area of 8,226 hectares with 62.4% forest cover. After 1989, the state owned land was restituted by the original owner, and presently all forests belong to the Roman Catholic diocese in the town of Spišské Podhradie; the forests are managed by a professional company. The forested area has an elevation span ranging from 382 to 1,544 m a.s.l. Even-age coniferous forests constitute more than 90% of the area, with a 77% share of spruce and admixture of silver fir and larch. A uniform shelterwood management system with a rotation period of 100-160 years is applied in the current management. Natural and artificial regeneration is combined to ensure desired stand regeneration.

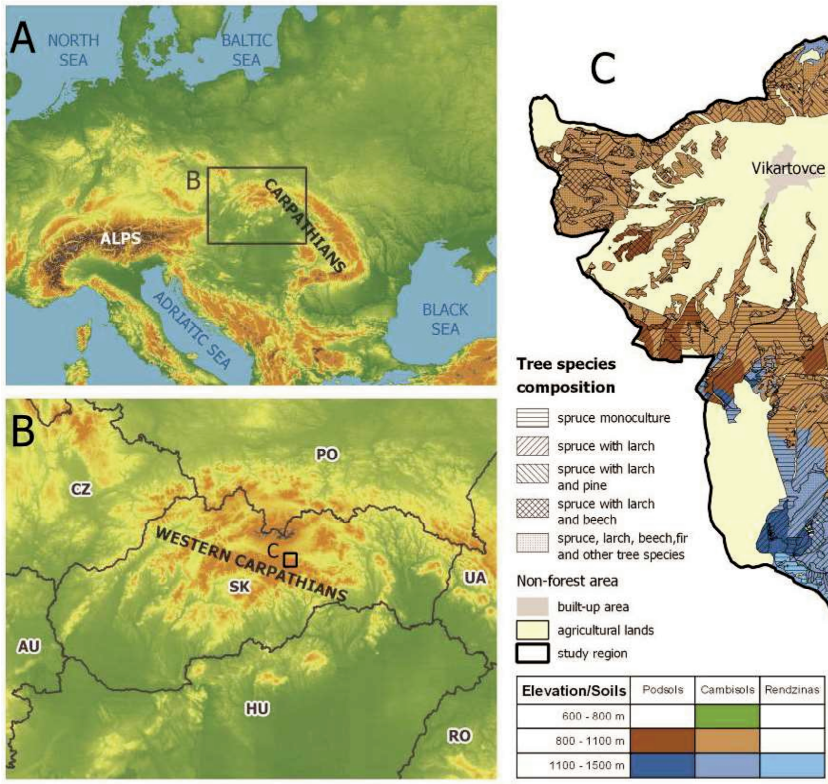

Figure 3: Position of the Goat Backs, Mts. model region in Europe (A, B), regional forests, main soil types and elevation zones (C).

Damage caused by abiotic factors, especially by wind or snow followed by bark beetle outbreaks frequently affects the regional forests. Since the year 2003, salvage logging has accounted for almost 100% of the total volume of harvested timber. The average annual volume of timber harvest between 2002 and 2011 exceeded 140,000 m^3.

The main ecosystem services provided by the forests in the Goat Backs Mts. are timber production, game hunting and recreation. Energy biomass production is of certain importance as well, though no special management supporting this function is applied. Biodiversity maintenance, carbon accumulation and protection from gravitation hazards are currently of minor importance; however, a growing involvement of diverse stakeholder groups (municipalities, environmental organizations, etc.) along with a growing recognition of forests` multifunctionality increase the importance of these services. The natural conditions of the area imply that the protection from gravitation hazards is of marginal importance only.

2.4 Management and Data Acquisition

2.4.1 Montafon, Austria

In this CS area all harvesting activities are carried out using skyline logging systems. Skyline tracks are positioned diagonal across the slope and extraction distances are typically over 500m. Maximum lateral yarding distances are 25 m left and right of a skyline track which defines the working area for each individual set up. A track of 5m width is cleared of all trees (>10m height) for establishing the skyline track. The working area is managed all along the slope according to current prescriptions (see section 2.5.2) to balance revenues and high expenses that arise from the cable yarding operation. This will result an increasingly uneven aged stand structure and analysis on current stand levels will not deliver informative results any more. After analyzing possible skyline setups current stands were merged into 18 units taking into account the existing forest road network and suitable shape of the terrain (see Figure 4).

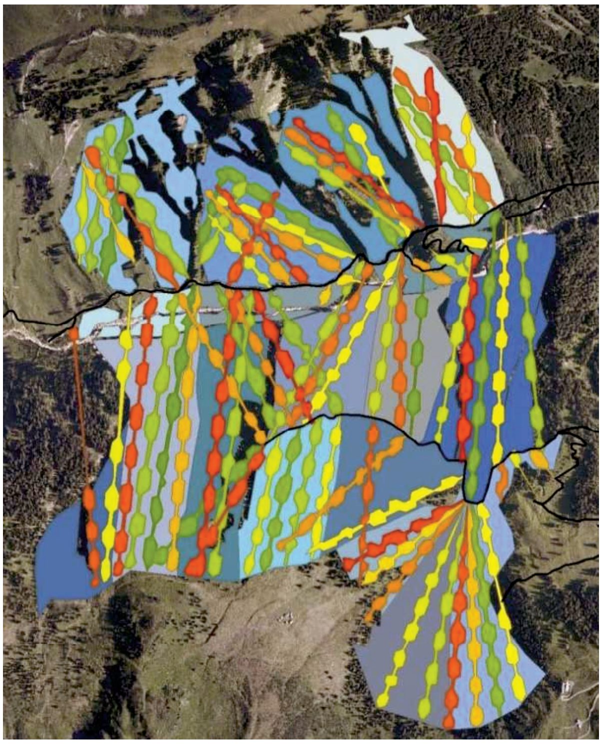

Figure 4: Harvesting units in the Austrian CSA (shades of blue) with skyline tracks according to business as usual (color palette green to red represents early to late harvests in the simulation period).

The size of the 18 harvesting units varies between 4 and 12ha. Tree and stand data was acquired by both terrestrial and aerial inventory methods: A terrestrial inventory was carried out using angle-count sampling on a base raster of 50x50m, measuring at least 8 inventory plots per unit to gather information about basal area per tree species, diameter distributions, as well as a description of regeneration and soil attributes. High resolution LiDAR data was used to derive a normalized crown model and a volume map (Hollaus et al. 2006, 2007). Based on this information an algorithm calculated single tree level data including spatially explicit mapping of the trees (see Maroschek et al. 2014). The resulting virtual stands reflect the real forest structure.

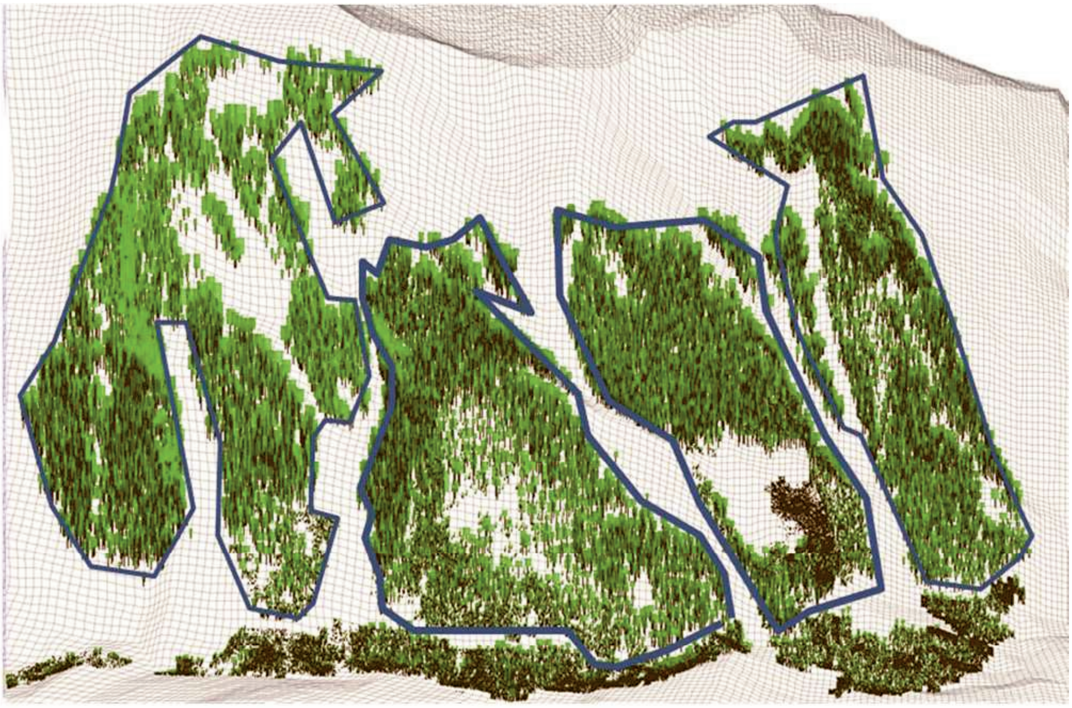

Figure 5: South slope of the Austrian CSA, showing four harvesting units and forest structures at tree level projected on a digital terrain model.

2.4.2 The Goat Backs Mountains, Slovakia

Forest stands were selected using the digital forest management plans and database of site data (soil, relief, etc.) to represent the natural conditions in the Slovakian CSA (meeting the concept of the representative stand types, RSTs). The field inventory was conducted in 2011. One sample plot sized 0.045 ha (a circle with a 12 m diameter) per hectare was established in each pre-selected forest stand; hence the number of sample plots depended on stand size. Diameter of all living trees was measured in each sample plot, and tree distribution in 1 cm diameter classes was evaluated for each tree species. The height of 6 trees with average stem diameter as well as the height of both the thinnest and thickest tree was measured in each sample plot as well. In addition, the ratio of dead and living trees was evaluated. A single soil sample was taken from each plot, and stone fraction and soil grain class was evaluated. The collected data were used to calculate stand density, species composition, mean height and diameter, and site class for each stand and tree species, total stand volume, and volume per hectare.

2.5 Growth simulation and Scenarios

2.5.1 Climate change scenarios

Five climate change scenarios and a stable climate scenario (baseline) were used to drive the forest development simulations in the Slovakian CSA. Observed climate data collected from 19 meteorological stations during the period 1961-2009 distributed inside and in the vicinity of the CSA were used for scenario downscaling and for the generation of a stable (baseline) climate. The five climate change scenarios were used to build one average climate change scenario. In the following, this average is referred to as the A1B scenario. The scenarios were designated for 3 elevation zones of the study region (650, 950 and 1.250 m a.s.l.) and 3 expositions. Spatial variability of changes (in terms of differences between scenario and the baseline) across the region is negligible. As the model used for forest dynamics simulations is not sensitive to relief exposition, the scenarios generated for various expositions within one elevation zone were averaged.

There are significant inter-scenario differences in both air temperature and precipitation by the end of the century (2071-2100). While the projected temperature increases are in the range of 1.9-4.9°C, precipitation change ranges from -10% to +35% of the baseline climate. A coupled effect of such changes can result in a strong variability of water availability and potentially diverging effects on tree growth and mortality.

In the Austrian CSA a baseline climate (C0) and five transient climate change scenarios (C1 to C5), each consisting of a 100-year time series 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 1961-1990 from the meterological 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 2004). Mean historic climate at 1,000 m a.s.l. is 6.2°C MAT and 1,150 mm annual precipitation with 840 mm 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. The five climate change scenarios are then used to build an average scenario.

2.5.2 Montafon, Austria

To analyze the consequences of alternative management strategies with respect to the provision of various ES under climate change four different management scenarios (see below) were simulated under two climate scenarios (BL, A1B) using the PICUS forest ecosystem modeling tool. PICUS is a hybrid forest gap model that builds on a 3D structure of 10 x 10 m patches, extended by crown cells of 5 m height and delivers growth and yield data. Interactions between patches are considered with regard to a three-dimensional light regime and spatially explicit seed dispersal. Tree population dynamics emerge from growth, mortality and reproduction and are calculated based on monthly input data. Management can be performed spatially explicit, using a GIS interface.

Scenario setup: In the growth and yield simulations only mortality induced by competition was considered. In the PICUS model mortality is calculated as a stochastic process on individual tree basis, taking into account tree age, nutrition, climatic factors and competition (Lexer and Hönninger 2001). To create input-data for YAFO mortality was modified to exclude external factors such as snow break, wind throw or lightning strike for single tree death.

While factors such as bark beetle infesting and browsing can be included in PICUS (Lexer and Hönninger 2001; Seidl et al. 2005, 2007), those factors were excluded in this step, as disturbance-induced mortality will be considered based on survival time probability within the YAFO modelling framework.

Simulations are run over 85 years and delivered in 5 year periods.

Scenario 1: No management

Growth and yield simulations were carried out for 90 years without silvicultural interventions and only natural regeneration.

Scenario 2: Business as usual

For simulating growth and yield data from the business as usual scenario (BAU) along the skyline track (see Figure 4), patches of about 1,000-1,500 m^2 are harvested with a total area of 33% of the potential area accessible per skyline track. Patches vary in size and shape and must meet the following limitations: minimum width of patches: 5 m, maximum distance in slope direction of cutting area must not exceed 30m. Only trees (>20 cm DBH) on the patches are harvested. Adjacent skyline tracks have to be harvested in alternation to extend patches only after regeneration is secured. The sequence of skyline setups is planned aiming at areas with uniform stand structures and high stocking volume to foster uneven-aged structures and create revenues for cost intensive harvesting operations. Furthermore the skylines are spread out on the landscape to have low visual impact of harvests. Areal turnover is about 250 years and harvests are equally distributed over the simulation period, which results in annual harvests of 0.84 ha/y, a number that equals one skyline track of 500m length for the CSA. Because of the steep slopes and the high demands regarding protective services, no thinnings or any other management operations are simulated.

Scenario 3: Light thinnings

On the whole working area of skyline tracks 20% of stems in diameter class 20-40 cm are harvested. Thinnings are carried out once per turnover cycle of 250 years and are the only management activities simulated. In this scenario no final harvests were simulated in PICUS, to allow derivation of an optimized decision on harvest activities within YAFO. The same skyline-track-setup is used as in business as usual scenario, but thinnings are carried out in earlier stand development phases. In average the area annually thinned is 1.85 ha (equals one skyline track of 500 m length, where only about 75% of the area accessible is harvested because of overlaps of the skylines.

Scenario 4: Moderate thinnings

For simulating growth and yield data under a “moderate thinning” regime, 40% of stems in diameter class 20-40 cm are harvested in each harvesting unit. All other details are similar to those described in scenario 3, “light thinning”.

For the ingrowth tables the stand types classification is as follows:

- (1) spruce mono-species type: spruce > 95% basal area
- (2) mixed conifers type: conifers > 95% BA
- (3) mixed forest type 1: conifers dominated: 5% < broadleaved BA < 25%
- (4) mixed forest type 2: broadleaved > 25% BA.

Each simulation unit is assigned to one of the stand types according to the basal area shares of the species. Ingrowth tables are depicting the forest growth after a harvesting activity for each stand type for baseline climate and CC scenario. As the timing of the harvests is not known as an input variable, but rather the result of optimization a modified climate is used to depict medium change of climate conditions over the whole simulation period in a constant way.

We chose standing and harvested volume and revenues of timber by species as indicators for timber production. High stocking volume of timber also offers good protective functionality against rockfall and landslides. However, well planned harvesting activities are needed to ensure small scaled regeneration in currently overaged forest areas and therefore guarantee steady protective functionality. Conservation services are depicted by diversity (representing both structural heterogeneity and species diversity of stands). Carbon aboveground represents Carbon storage services.

2.5.3 The Goat Backs Mountains, Slovakia

Tree growth simulator SIBYLA (Fabrika and Ďurský 2005) was used for the growth and yield simulations in this CSA. SIBYLA is an empirical, individual-tree-based, distance-dependent forest growth and yield model based on the SILVA model (Pretzsch et al. 2002). The model simulates the growth of individual trees and evaluates inter- and intra-species competition among trees. The growth sub-model was originally designed by Pretzsch and Kahn (1998). Growth response to environmental parameters was formalized according to Kahn (1994). The mortality sub-model was developed by Ďurský et al. (1996) and Ďurský (1997). The model’s temporal resolution is 1 year. To make it representative of Central Europe, the SIBYLA model was parameterized using 1,189 forest plots from the Slovak forest monitoring network (National Forest Centre, internal data), which included 7,358 spruce, 1,137 fir, 1,181 pine, 9,213 beech, and 3,444 oak trees. Additional site- and stand-specific calibration using observed tree heights, diameters, and mortality can be applied. The model's climate sensitivity makes it useful for climate-change impact studies (Hlásny et al. 2011, 2014).

The ingrowth tables used to drive the forest development in YAFO were produced using the SIBYLA model by simulating the development of the main tree species compositions growing in the region. The composition of the model stands is as follows:

- (1): spruce 100%
- (2): spruce 50 %, pine 30%, fir 20%
- (3): spruce 50 %, pine 30 %, beech 20%
- (4): spruce 50%, beech 30%, maple 20%.

The simulations have been run under the baseline climate and the climate change scenario. In the latter case, an ingrowth rate was calculated by calculating an average output of the simulation runs driven by the five climate change scenarios described above. Although the model allows for the simulation of the effects of increased mortality rates related to disturbances, we run the simulations only with mortality related to the competition; the effect of disturbances is considered in the optimisation procedure performed by YAFO.

Scenario 1: No management

No management interventions were applied, and undisturbed stand development was simulated. Inherent stand mortality (no disturbances) and natural regeneration modes were activated.

Scenario 2: Business as usual

Even-aged BAU management is implemented in the SIBYLA model in the form of time series, which prescribe the tree removal and planting interventions in 5-year steps (forest growth is simulated in one-year step). Both natural and artificial regeneration is simulated. While the natural regeneration module is implemented in the SIBYLA model, artificial regeneration is still under development. Therefore, we introduced artificially regenerated trees into the stands semi-manually. As SIBYLA simulates growth of trees higher that 1.3 m only, we generated artificially regenerated trees with age of ca 10 years in pre-defined positions ca 10 years after planting. Tending is implemented as a reduction of stocking when an actual stocking exceeds the value prescribed by the management plan. Thinning of different types is implemented (from above, from below, neutral) using selection of trees by database queries.

To mimic the harvesting procedure which is applied in the CSA, the harvesting is simulated in strips with width based on actual yield class (Figure 6). Time between harvest cycles is 5-10 years in each stand. One third of the stand is harvested in each cycle. In case of stands with beech or fir admixtures, two phase harvesting is implemented: firstly, stocking is reduced to 0.5 (relative to the theoretical full stocking volume in given site and age) to support regeneration; in a second step the remaining trees are harvested after a ten-year period.

Spruce monocultures: The management supports the transformation of spruce monocultures to more diverse stands. Tending is done to reduce stand density to 0.9. Moderate thinning from below is applied. Final cut is done in strips, in time intervals of 10 years. Only one third of stand area is harvested in a given year.

Stands with admixture of beech and fir: Tending is carried out to reduce stand density to 0.9. Moderate thinning from below followed by more intensive thinning from above is applied. Final cut is done in strips, in time lag of 10 years. Final cut is divided into two phases: reduction of the stock to 0.5, and removal of the remaining trees in a strip cut. Beech and fir are supported in the regeneration.

Figure 6: Aerial view of spatial arrangement of the BAU management operations in the Slovakian CSA. Harvesting, planting, thinning etc. are organized in strips along the dip lines. The width of a strip does not exceed a double of height of a mature tree.

Scenario 3: Light thinnings

Moderate thinning from below is applied. No final harvest is conducted.

Scenario 4: Moderate thinnings

Intensive thinning from above using constant reduction of density to 0.7 is applied. Close to selective thinning in transition to close-to-nature forestry; without the final harvest.

3 Results

3.1 Montafon, Austria

The stands in the Montafon CSA are characterized by a low increment (near or slightly below zero due to overaging of the stands). Even with a low interest rate of 1.5% and a maximum allowed harvest rate of 10 $m^3/(ha*y)$ the optimization tool YAFO chose to harvest two thirds of the existing stands within 8 periods or 40 years nearly completely and to partially establish new stand generation so that the stocking volume in total is reaching 191 m^3/ha in period 16 (in 80 years, see Figure 7).

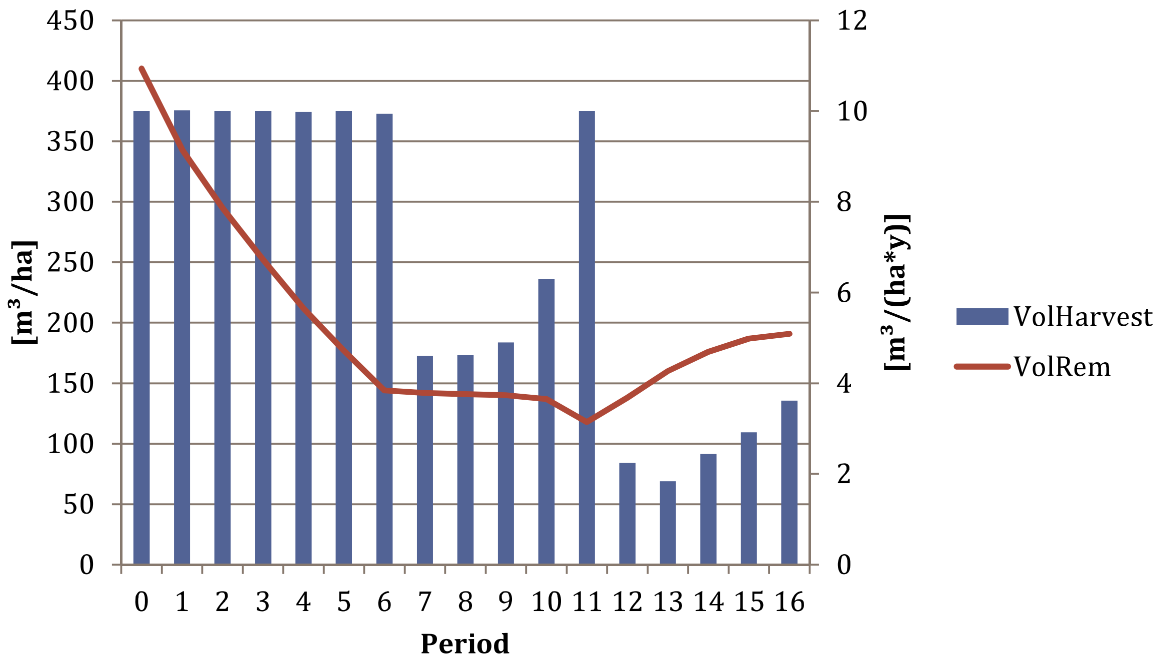

Figure 7: Development of the growing stock (VolRem) and the amounts harvested (VolHarvest). BL scenario. Results from the Austrian CSA

In the BL case the tool suggests to reduce the stocking volume of the stands in long-term final harvests (over 30 years) to 140 m^3/ha to establish new ingrowth. With this strategy the amount of salvage logging can be reduced from around 2 to 1 $m^3/(ha*y)$ or from 20% to 10% of the initial logging volume. The increment rate rises to around 5.5 $m^3/(ha*y)$ within 50 years. The management options are split up more or less equally over all areas splitting each stand individually and assigning parts of the stand areas to different management options. The tool is treating 29% of the timber volume according to management scenario 2 (BAU), 26% according to scenario 3 (light thinning), 23% according to scenario 4 (moderate thinning), and 22% according to scenario 1 (no management). The ingrowth then is established according to stand type 2 (spruce-fir mix).

In the climate change scenario (A1B) the recommendations would change: The growing stock would be reduced to even 96 m^3/ha (within 35 years) to establish new ingrowth, finally reaching 317 m^3/ha in period 16 (in 80 years, see Figure 8), a much higher final standing timber volume than without climatic change. With this strategy the present low increment rises to slightly above 8 m^3/(ha*y) within 55 years. The ratio of the BAU treatment increases initially to 35%. 19% are treated according to scenario 3 (light thinning), 25% according to scenario 4 (moderate thinning) and 21% according to scenario 4 (no management). In the A1B case the ingrowth should be established according to stand type 3 (spruce-fir-beech mix). The strategy results in a two-phase shape of the harvest schedules. In phase 1 (reducing the stocking volume), lasting for the first 35 years, in every period 10 m^3/(ha*y) are harvested. Then management switches to increase the growing stock. So in phase 2 the harvests are reduced to a level of between 1 and 5 m^3/(ha*y).

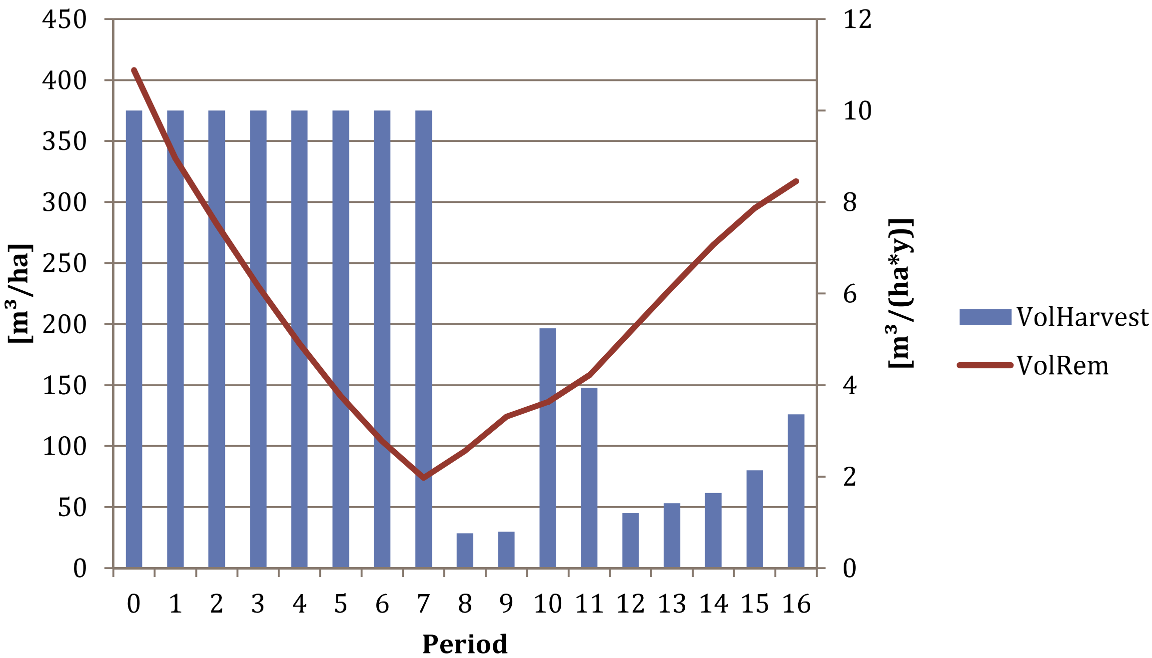

Figure 8: Development of the growing stock (VolRem) and the amounts harvested (VolHarvest). A1B scenario. Results from the Austrian CSA

In a second optimization a minimum stock of 250 m^3/ha was introduced as a constraint, simulating a protection against avalanches and rockfall as an ES that is provided by keeping higher levels of growing stock. The minimum stock was derived as following: The overall minimal demand for a sufficient avalanche protection in a forest is a crown cover rate of at least 50% (Frehner et al. 2005). As in the CSA rotations up to 250 years are used, the average age can be estimated as about 80 years. Yield tables for spruce like Wiedemann class II report a growing stock of about 500 m^3/ha for this age (Schober 1987). So a crown cover rate of 50% corresponds to at least 250 m^3/ha.

In the BL case the initial growing stock will be reduced to around 280 m^3/ha within 4 periods or 20 years to maintain the required 250 m^3/ha after harvests (see Figure 9). After that initial phase of volume reduction with harvests of 10 m^3/(ha*y) a second phase starts with constant growing stock levels and harvest rates between 3.5 and 6 m^3/(ha*y). In the A1B case the schedule looks similar, but harvests are shifted more into the future (see Figure 10). The ingrowth management differs as well. Whereas in the BL case the ingrowth is established according to stand type 2 (spruce-fir mix) and 4 (beech-hardwood type), here stand type 3 (spruce-fir-beech mix) is chosen by the optimization approach.

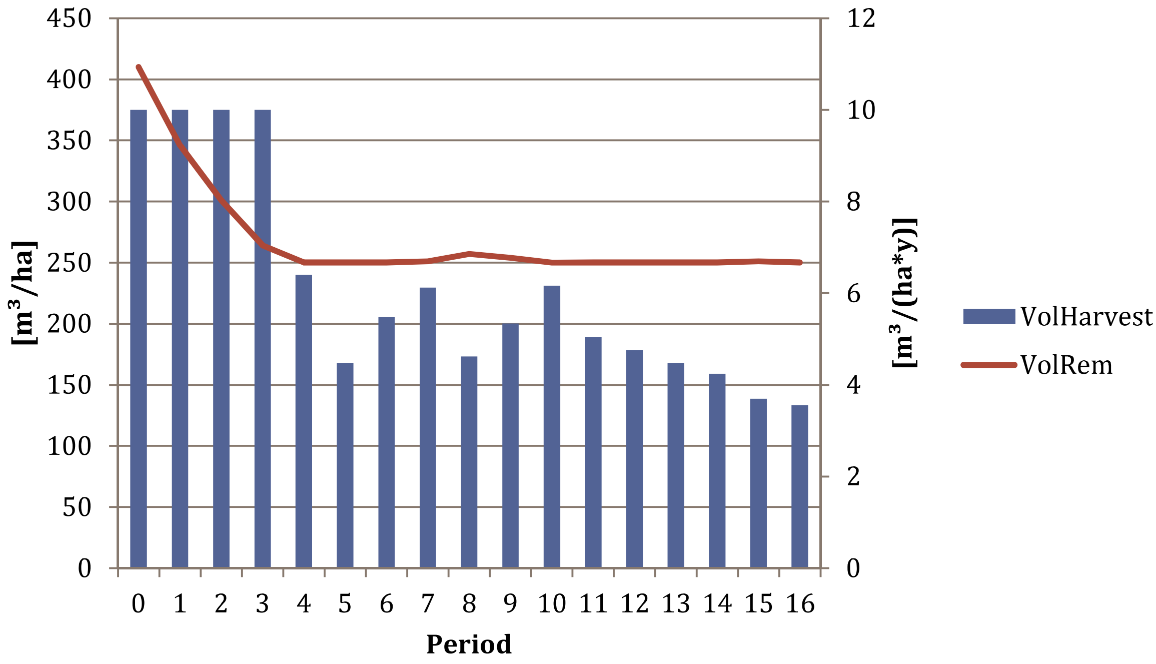

Figure 9: Development of the growing stock (VolRem) and the amounts harvested (VolHarvest). BL scenario. Results from the Austrian CSA. Additionally a minimum stocking volume of 250 m^3/ha is required.

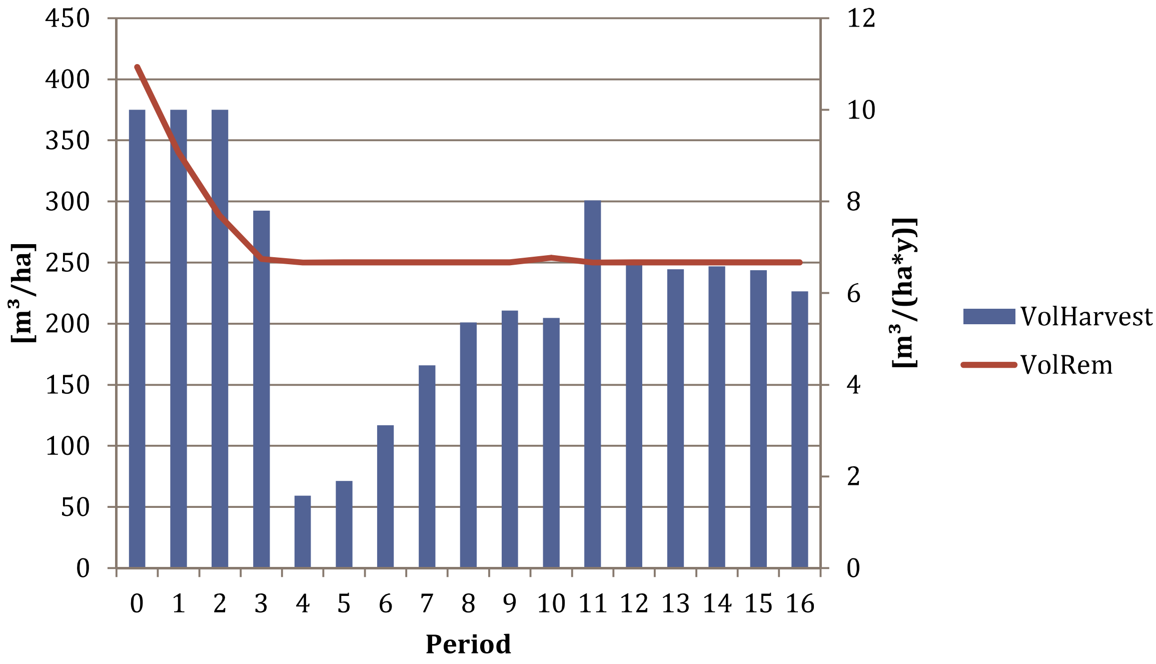

Figure 10: Development of the growing stock (VolRem) and the amounts harvested (VolHarvest). A1B scenario. Results from the Austrian CSA. Additionally a minimum stocking volume of 250 m^3/ha is required.

In the BL case the provision of that minimum stock influences the risk in a desirable way as the standard deviation of the NPV is decreasing from 74% to 50%. In the A1B case the risk is rising clearly from 59% to 124%. Accordingly, as we assume the conditions of the BL case the provision of the minimum stock reduces the returns from -15 to -21 EUR/(ha*a) but does also slightly reduce financial risk. In the A1 case both variables are influenced negatively by providing the ES service and we calculate lower returns with higher risks.

The comparison of the annuities shows that the provision of the exemplary ES "protection against avalanches and rockfall" costs 6 EUR/(ha*a) in the case of the BL scenario and 14 EUR/(ha*a) in the case of the climate change scenario.

Table 1 gives an overview of the financial results over the four optimization runs. In the A1 case positive but small returns can be achieved whereas in the BL scenario the annuities are negative. The reasons being generally low timber prices combined with high harvesting costs due to the topographic conditions. As returns are near zero, the fluctuations caused by natural disturbances and timber price changes lead to noticeably high relative standard deviations (between 50% and 124%). The better growth of the ingrowth in the A1 case helps to raise the returns to positive results.

Table 1: Financial results of the Montafon CSA. Net present value, standard deviation (STD), standard deviation relative to the NPV (variation coefficient VC), Value at risk (the value of the objective function), annuity and standard deviation of the annuity.

	Net Present Value			Value at Risk	Annuity	
	[EUR/ha]	STD	VC	[EUR/ha]	[EUR/(ha*a)]	STD
BL	-731	540	*74%*	-1,986	-15	11
BL VolMin 250	-1,008	504	*50%*	-2,180	-21	11
A1	1,127	661	*59%*	-411	24	14
A1 VolMin 250	467	580	*124%*	-881	10	12

3.2 The Goat Backs Mts., Slovakia

As there are high salvage ratios in this case study region we also introduced a maximum harvest volume of 10 m^3/(ha*a) or 50 m^3/(ha*period) to avoid an intensive volume reduction of the remaining stands within a couple of periods.

Figure 11 shows the biophysical results of the optimization for the BL case. The initial volume of 400 m^3/ha (or 350 m^3/ha after harvests) has been reduced to 152 m^3/ha in periods 9 and 10 (i.e. within 45 to 50 years) and rises again to 246 m^3/ha in period 18 (in 95 years). Over the whole simulation period the restricted maximal harvest amounts of 10 m^3/(ha*y) are used. By reducing the stocking volumes new ingrowth is established reaching 212 m^3/ha in period 18. That means nearly all initial existing stands are harvested and transferred to a new stand generation. The initial salvage logging volume of about 6.5 m^3/(ha*y) is reduced to below 2.6 m^3/(ha*y) in periods 5 to 18. After a phase where the management suggestion is focused on final harvests (between periods 4 to 10) a second phase begins where mainly thinnings are executed. This strategy helps to raise the increment from initially 4.5 m^3/(ha*y) to a final level between 12.0 and 13.0 m^3/(ha*y).

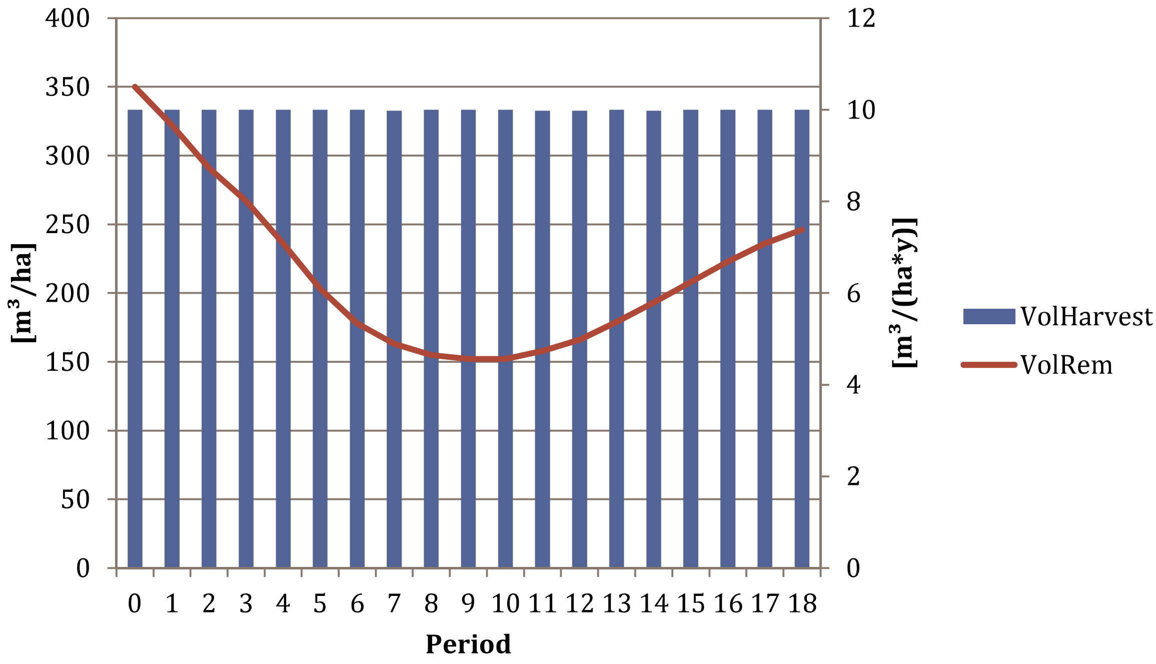

Figure 11: Development of the growing stock (VolRem) and the amounts harvested (VolHarvest). BL scenario. Results from the Slovakian CSA

Initially (in simulation period 0) 45% of the harvested timber is managed according to the scenario "moderate thinning". 28% is harvested according to "current management", 22% according to "no management" and 6% according to "light thinning". But these ratios are highly dependent on the investigated period. There is a tendency that in most cases "moderate thinning" and "current management" are the preferred options. Within the simulated ingrowth stands the stand type 3 (50% spruce, 30% pine, 20% beech) is clearly preferred.

As the differences between the BL and A1B climate scenario are small we show them in a different representation. As such, Figure 12 shows the differences of the harvest volume between the baseline and the climate change scenario in each period. The harvested amounts are additionally split by the four different management scenarios. There is a clear tendency for increasing differences between the two climate scenarios in the second part of the investigated time horizon, with more harvests under climate change conditions. Also, in the second half of the analyzed time horizon, the variant "no management" becomes less important whereas increasing amounts of timber are harvested according to the close-to-nature management scenario "moderate thinning" as well as the "current management" scenario. In the long term (i.e. ingrowth management) stand type 3 dominates as it does in the BL case.

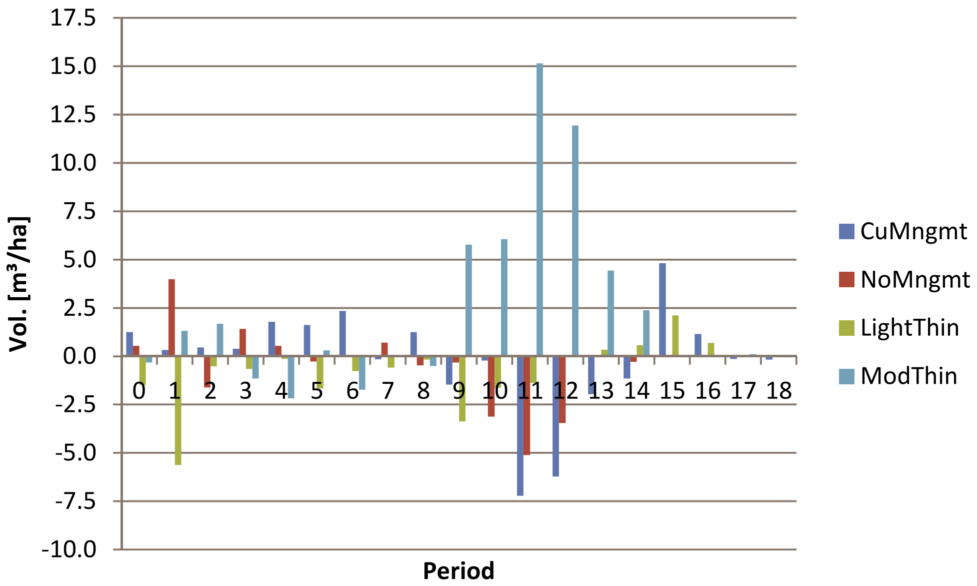

Figure 12: Difference of the amounts harvested between the climate change scenario and the baseline scenario. A positive value means more harvests under climate change conditions. "CuMngmt" is current management (BAU), "NoMngmt" is no management, "LightThin" is light thinning and "ModThin" is a moderate close-to-nature thinning.

Table 2 gives an overview of the financial results. Comparing the lines "BL" and "A1B", the average annuity is reduced just slightly from 359 to 350 EUR/(ha*y). In both cases the standard deviation is at 18 to 19 EUR/(ha*y) or 5.1 to 5.5%. This is an effect of the natural growth that is only slightly reduced under climate change conditions.

In the second optimization design a minimum stocking volume of 250 m^3/ha was introduced as a constraint, simulating a protective ES function like avalanches, rockfall, soil erosion, local climate regulations, water regulation or wildlife habitat that is provided by high stocking volumes. The "u shape pattern" of the volume development is graduated by this restriction leading to a temporarily reduction of the harvest rate to 4.8 m^3/(ha*y) in period 5 (in 25 years) that gradually rises again to 10.0 m^3/(ha*y) in period 10 (in 50 years, see Figure 13 for the BL case).

Figure 14 shows the same for the A1 case. The result is quite similar to the BL case. However, due to the reduced growth under climate change conditions the reduction in harvests is more severe. Also it is not possible to raise the volume considerably above the required 250 m^3/ha at the end of the investigated time horizon. The tree selection within the ingrowth is always according to stand type 3 (50% spruce, 30% pine, 20% beech).

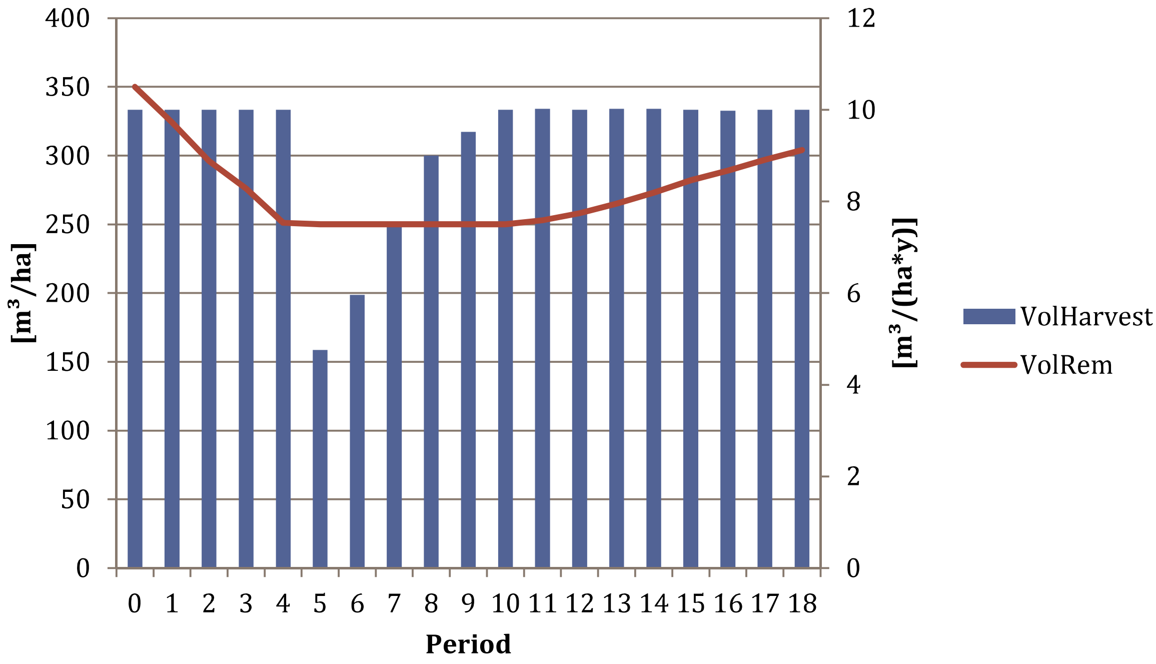

Figure 13: Development of the growing stock (VolRem) and the amounts harvested (VolHarvest). BL scenario. Results from the Slovakian CSA. Additionally a minimum stocking volume of 250 m^3/ha is required.

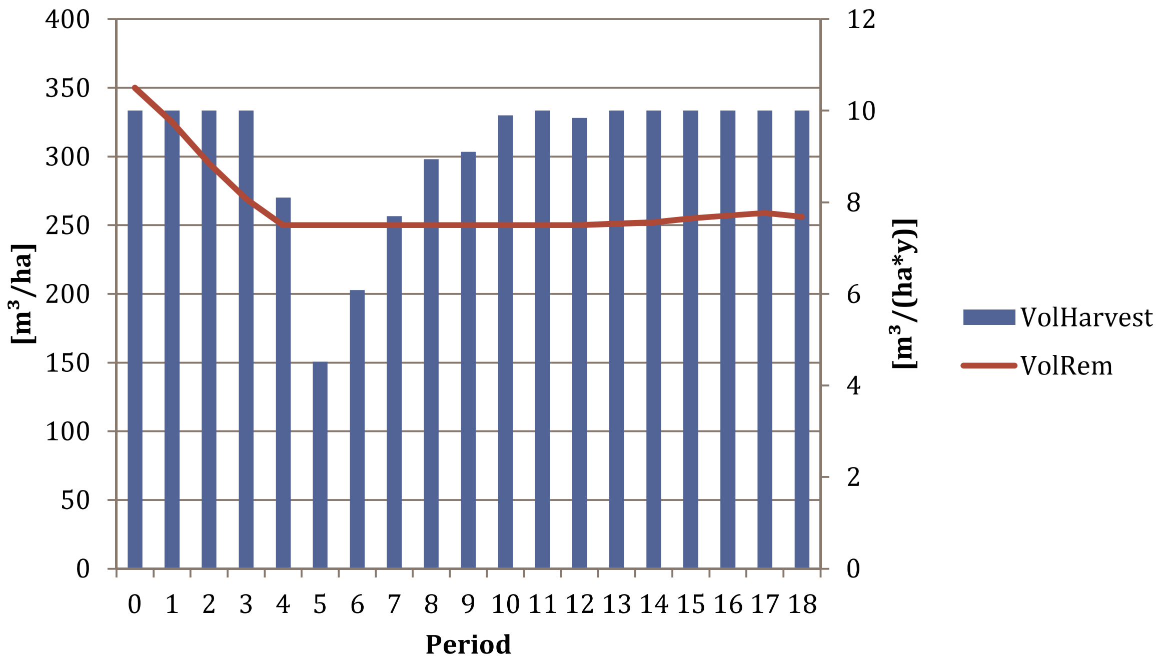

Figure 14: Development of the growing stock (VolRem) and the amounts harvested (VolHarvest). A1B scenario. Results from the Slovakian CSA. Additionally a minimum stocking volume of 250 m^3/ha is required.

The comparison of the annuities shows that the provision of the ES costs 45 EUR/(ha*y) in the case of the BL scenario and 56 EUR/(ha*y) in the case of the A1B scenario. That means, there is only a slight difference between the scenarios. Under climate change conditions the costs rise from 12% to 16% of the returns. In total, the costs for the provision of the ES are significant.

Table 2: Financial results of the Slovakian CSA. Net present value, standard deviation (STD), standard deviation relative to the NPV (variation coefficient VC), Value at risk (the value of the objective function), annuity and standard deviation of the annuity.

	Net Present Value			Value at Risk	Annuity	
	[EUR/ha]	STD	VC	[EUR/ha]	[EUR/(ha*y)]	STD
BL	18,117	931	*5.1%*	15,951	359	18
BL VolMin 250	15,864	888	*5.6%*	13,799	314	18
A1B	17,658	969	*5.5%*	15,404	350	19
A1B VolMin 250	14,823	883	*6.0%*	12,768	294	18

4 Discussion & Conclusions

Our research explored the options for linking two forest dynamics models (PICUS and SIBYLA) driven by an ensemble of climate change scenarios with a forest management optimizer (YAFO) to analyze possible responses of management to climate change.

The Austrian CSA showed a positive influence of the climate change scenario on the results – in the sense of a better economic result. A possible explanation is the fact that the growth of the trees increases under climate change scenario A1B leading to positive annuities compared to the BL climate scenario (minus 15 and plus 24 EUR/(ha*y) respectively).

In both cases the recommendations that arise for the practitioner are to reduce the growing stock of the currently overaged stands to establish new ingrowth leading to an overall reduction of age and related risk as well as an increase in growth. This reduction should be done slowly over a planning period of 35 to 50 years to further reduce financial and biophysical risks that increase with increasing aerial size of harvesting activities.

If a minimum growing stock of 250 m^3/ha is to be maintained volume reduction has to be stopped after 20 years to allow the introduction of a management regime focusing on constant levels of growing stock on the enterprise level. To allow for such a beneficial development, around 40% of the total area (64 ha) have to be managed for the establishment of regeneration raising the increment rate so that within 60 years an annual increment and harvest rates of about 5 m^3/(ha*y) become possible.

Additionally, our analysis shows the influence of a changing climate on tree species selection for the ingrowth. In the BL scenario spruce-fir mixtures, defined as >95% of basal area comprised of conifers, and beech-hardwood mixtures, defined as >25% of basal area comprised of beech are dominating, whereas under scenario A1B the tree composition is switching to more spruce-fir-beech mixtures with a ratio of 5% - 25% in basal area made up of beech. That means, under climate change conditions the admixing of hardwoods to softwood stands should be emphasized to count for the changing risk and growth conditions in the Austrian CSA. This result is comparable with the 20% beech admixture necessary for the reduction of financial risks found by Roessiger et al. (2011) as well as a 7% admixture of beech into spruce stands described by Griess et al. (2012), to achieve a distinctive reduction of risk.

In the Slovakian CSA the results show similar main patterns as those for the Austrian CSA. The recommendation is to initially reduce growing stock to around 150-200 m^3/ha to improve increment rates and to reduce risk, i.e. the ratio of salvage logging, leading to annuities of 280 to 320 EUR/(ha*y). On the contrary to the Austrian CSA, the harvest rates can be held constant over the entire planning horizon as increment rates are much higher. For the management of ingrowth a tree mixture of 50% spruce, 30% pine and 20% beech is preferred over the other options (see section 2.5.3). To compensate for the reduced growth, in the A1B climate scenario this should be accompanied by managing more and more stands according to “current management” or “moderate thinning” reducing the area without any management.

If a volume minimum growing stock of 250 m^3/ha is to be maintained, harvests have to be reduced to around 6 m^3/(ha*y) during the first 25 years. After that they can be gradually be increased back to the initial 10 m^3/(ha*y) over a time span of 30 years as the increment rate increases over time.

The most interesting result for Slovakia is the increasing relevance of the “moderate thinning” and “current management” scenarios under a changing climate. One explanation is that due to the slightly reduced growth in that case the additional increment of the remaining trees induced by slightly more intensified thinning can compensate losses in growth better than any other management option.

The comparison of both CSAs shows that it is in fact possible to derive some general recommendations for optimum forest management strategies under a changing climate. We can recommend the reduction of growing stock levels to improve ingrowth rates and shifting the tree selection within the ingrowth towards hardwood ratios of up to 20%. Our results correspond with the findings of Griess & Knoke (2013) or Brang et al. (2014) who derived 6 principles for enhancing the adaptability of forests within close-to-nature silviculture. Our results confirm the principles of increasing tree species richness, increasing structural diversity, replacing high-stand risks and reducing average growing stocks for a successful sustainable forest management in the long term.

However, some problems remain unresolved, and are subject to further research: The fact that the forest dynamics models (PICUS and SIBYLA) are not interactively connected with the optimizer (YAFO) required to deliver model output in form of an ingrowth table (specific to each climate change scenario and providing data for different ingrowth options). This output table governed the growth process in the optimizer after thinning or harvesting operations. So, the differences in growth process governed by an ingrowth table and by the forest dynamics model should be kept in mind. If a direct bi-directional interface between the two parts that our methodology requires (simulation + optimization) would be made available it would be possible to integrate changes in growth due to thinning or harvesting directly.

Furthermore, the decision the optimizer makes regarding ingrowth is highly dependent on the simulated time horizon. If another tree mixture would be superior in the long run the model cannot include this in its decision. So the proposed management strategy has always to be seen as the best decision based on what we know today. If knowledge changes the planning has to be updated. A limitation that applies to all scientific outputs. To make inclusion of such changes into future research easier it would be desirable to develop the interface mentioned earlier as well as to further develop growth & yield models to allow the production of stand information in a fast and reliable way. This could be done by further developing the necessary model parts with a focus on user friendliness, adaptability as well as computing capacity to reduce model runtimes.

Finally, the simplification of the effect a changing climate has on forest development has to be kept in mind when converting our findings into practical recommendations. While a comprehensive and detailed evaluation of the tree growth subject to climate change showed differential responses along the elevation gradient (e.g. Hlásny et al. submitted), the outputs of the optimization presented here were produced assuming an average response for the entire CSA based on a single ingrowth table. Therefore, further modifications of the methodology would be needed to allow using outputs as a direct guide for forest management planning. A possible solution could be to run the optimization separately for several elevation zones which show differential growth response to climate change.

Even though the limitations named above are important and will need further work to be fully overcome, our research presents first findings of its kind, combining information from different areas and forest dynamics models to derive optimized management plans for larger areas. Our work allows a comparison of the differences in forest development over a large European mountain area and can be seen as a first step towards a wider analysis of what climate change will mean for our European forests, what we can do to adapt our management towards upcoming changes as well as towards finding ways to allow consideration of ecosystem services in optimized forest management planning on larger scales. Additionally, our research can be seen as a guideline regarding what information is necessary, to develop improved forest management models, an area of outstanding future importance. As the significant societal changes over the last decades and the emergence of new policies, (e.g. on biodiversity, bioenergy and climate change clearly) present the need to enhance sustainability of multipurpose forestry in the European Union.

5 Acknowledgements

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