# Multifunctionality in European mountain forests –

# An optimization under changing climatic conditions

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Word count of the manuscript: 5766

## Abstract

Forests provide countless ecological, societal and climatological benefits. With changing climate, maintaining certain services may lead to a decrease in the quantity or quality of other services available from that source. Accordingly, our research objective is to analyze the effects of the provision of a certain ecosystem service on the economically optimized harvest schedules and how harvest schedules will be influenced by climate change.

Based on financial portfolio theory we determined for two case study regions in Austria and Slovakia treatment schedules based on non-linear programming which integrates climate sensitive biophysical risks and a risk-averting behavior of the management.

Results recommend in both cases reducing the overaged stocking volume within several decades to establish new ingrowth leading to an overall reduction of age and related risk as well as an increase in growth. Under climate change conditions the admixing of hardwoods towards spruce-fir-beech (Austria) or spruce-pine-beech (Slovakia) stands should be emphasized to count for the changing risk and growth conditions. Moreover, climate change scenarios either increased (Austria) or decreased the economic return (Slovakia) slightly. In both cases, the costs for providing the ecosystem service “rock fall protection” increases under climate change. While in the Austrian case there is no clear tendency between the management options, in the Slovakian case a close-to-nature management option is preferred under climate change conditions. Increasing tree species richness, increasing structural diversity, replacing high-risk stands and reducing average growing stocks are important preconditions for a successful sustainable management of European mountain forests in the long term.

## Keywords

Forest management, ecosystem services, climate change, economic optimization, risk integration, management planning

# 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 often only their ability to produce timber is being considered in the economic estimation. Other ES like carbon storage provided by forests are rarely ever taken into consideration in research studies (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 (see Reid et al. 2006). Studies with a more quantitative approach to including the provisioning of ecosystem services into decision making on land-use include Nelson et al. (2009) and Goldstein et al. (2012), who evaluated landscape scenarios regarding the services they promise, as well as Bateman et al. (2013) who used landscape optimization approaches for the UK, while considering ecosystem services and climatic change. However, only few studies included uncertainties (see Uhde et al. 2015).

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 two case study areas (CSA) Montafon (Austria) and Goat Backs Mountains (Western Carpathians, Slovakia), which are addressed in the EU funded project ARANGE. The inclusion of an important ecosystem service is achieved through a constrained optimization, while multi-objective optimization would address various objectives more directly. We shall discuss the implications of our approach later.

Based on the portfolio theory (Markowitz 1952, 2010) we will determine optimal SFM strategies at stand level. Optimized spatially implicit 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.

# 2 Material & Methods

The CSA were selected to compare different environments for forest management. While the Austrian CSA cover only higher altitudes (>1000 m a.s.l.) the Slovakian CSA includes lowlands with higher productivity. We expect non-uniform impacts of climatic change on forest management in both CSA. Moreover, we wanted to include a CSA (Slovakia) where management is already very much driven by adverse natural events, such as wind or snow followed by bark beetle outbreaks. Here we expect that alternative recommendations are certainly needed for forest management.

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 panel discussions involving representatives of the CSA. All management scenarios (see figure 1) were simulated under a baseline (BL) climate scenario representing historic climate conditions of the period 1961-1990 and 5 transient climate change scenarios based on the ENSEMBLES project (see online supplement). 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 using “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 transient climate change scenarios from the period 2080-2100. For further details on data acquisition and growth simulations see the online supplementary material.

## 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. The maximum forecasting horizon is 20 periods. For this study we chose a period length of 5 years.

YAFO provides these two optimization algorithms: a net present value (NPV) optimization without considering any risk factors and a value at risk (VaR) maximization. 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:

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

with

$$n_{itus}^{(y)} \coloneqq p_{itus}^{(y)} - c_{itus}^{(y)} - f_{itus}^{(y)} \tag{2a}$$

$$k_{its}^{(y)} \coloneqq p_{its}^{k(y)} - c_{its}^{k(y)} - f_{its}^{k(y)} \tag{2b}$$

and the constraints:

$$\sum_{s} a_{it'1s}^{n} + \sum_{t=0}^{t'} \sum_{s} \left( a_{it0s}^{n} + a_{its}^{k} \right) = a_i \quad \forall i, t' \tag{3a}$$

$$\sum_{s} a_{its}^{k} = a_{it}^{k} \quad \forall i, t \tag{3b}$$

$$a_{itus}^{(n.k,y)} \geq 0 \quad \forall i, t, u, s \tag{3c}$$

$$\sum_{u} a^{ny}_{it'u} = \sum_{t=0}^{t'} \sum_{s} \left( a^{n}_{it0s} + a^{k}_{its} - a^{ny}_{it0s} - a^{ky}_{its} \right) \quad \forall i, t' \tag{3d}$$

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. The high index $k$ labels variables and parameters referring to salvage loggings. For the interest rate 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 describing the ingrowth. Their meaning is the same as those mentioned already. Constraint 3a 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 3b ensures that the salvage felling area in each period cannot be used as a thinning or final felling option. Constraint 3c prohibits non-negativity regarding the areas assigned to the various treatments. Constraint 3d 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 (MCS) 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 $F_Z$. In this study we used the p-quantile of 1%. So under the influence of risk the objective is defined as follows:

$$\max_{a} Z = F_Z^{-1}(p) \tag{4}$$

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 MCS. The MCS can use either fixed hazard rates or age dependent Weibull functions to incorporate the occurrence 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.

The variance of the last period is divided by five to account for the fact that the model cannot distribute its decisions in this period forward into the future as can be done in reality, because the model does not cover future periods. Taking the full variance of the last period into the model causes heavy harvests in the preceding period, whereas reducing the variance to zero lets the model try to avoid the harvests and to reach the risk-free last period with all the timber. The parameterization of this factor must balance these two opposing decisions in a reasonable way (Härtl et al. 2013).

For simulating ecosystem services like avalanche or rockfall protection optimization runs with minimum stocking volumes were done. 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 at least 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.

## 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). 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. 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).

## 2.3 Case Study Area: Goat Backs Mts., Slovakia.

The Goat Back Mountains are located in the Northeast Slovakia in the mountain range of the Central Western Carpathians. It covers an area of 8,226 hectares with 62.4% forest cover. 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-aged 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.

Damage caused by abiotic factors, especially by wind or snow followed by bark beetle outbreaks frequently affects the regional forests. 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.

# 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 2a).

In the baseline climate (BL) case the optimization approach 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 regime. 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 simulations suggest 29% of the harvested 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 2b), 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).

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.

In a second optimization a minimum stock of 250 $m^3$/ha was introduced as a constraint, simulating a protection against avalanches and rockfall, soil erosion, local climate regulations, water regulation or wildlife habitat that is provided by high stocking volumes.

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 2c). 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 2d). 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.

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 (standard deviation) 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 A1B 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 A1B 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 A1B case helps to raise the returns to positive results.

## 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 a too intensive volume reduction of the remaining stands within a couple of periods.

Figure 3a 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).

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 3c 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.

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 with a minimum stocking volume, 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 3b for the BL case).

Figure 3d shows the same for the A1B 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).

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.

# 4 Discussion & Conclusions

## 4.1 General

Our approach presents an optimization of harvest schedules under climate change and the provisioning of an important ecosystem service (protection against avalanches and rockfall). We choose two different case study areas for two reasons: First: one is in the Alpine region and the other in low mountain range, so that we can cover most of the typical mountain forests in Central Europe. Second: 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.

## 4.2 Climate change

Different to other approaches, such as Hanewinkel et al. (2010; 2013), the economic impact of climatic change has been modelled more mechanistically in our study. While the mentioned alternative studies use climate dependent presence/absence estimations for tree species to predict the economic impact of climate change on forestry, the climate scenarios affect the growth parameters and the survival curves directly. This leaves space for adapting the management accordingly, which depends in first place on economic considerations (expected return and risk).

## 4.3 Ecosystem services

While climatic change impacts on the growth rates and the survival probabilities, the ecosystem service is addressed through a constraint (minimum stocking of 250 m$^3$/ha). Advantages of this approach are the optimization perspective, which suggests management strategies at a minimum of opportunity costs. Also, the costs for providing the ecosystem service may be derived, which is important for discussions with stakeholders. Another advantage is that the constraint guarantees the required level, for example of the standing timber in our case. Thus, possibly very high levels of other services, such as timber production, cannot serve to compensate for smaller than demanded protective services.

There are only few studies including ecosystem services into optimization on landscape of larger scales. Nelson et al. (2009) and Goldstein et al. (2012) carried out scenario analyses at landscape scale considering a limited number of pre-defined scenarios. In contrast, Wise et al. (2009) imposed a carbon tax to take into account climate regulation services into land-use optimization. This study used a highly complex world dynamic recursive model including energy, economy, agriculture, land use, and land cover based on economic equilibrium in energy and agriculture markets. Bateman et al. (2013) carried out land-use optimization for the UK under the impact of climatic change and integration of ecosystem services. These were considered in the modelling through hypothetical financial payments, for example, for recreation. In contrast to the study by Bateman et al. (2013), our study has been more conservative, including the protective function via a constraint and not via estimated willingness to pay for a service. Our higher conservativeness might have the advantage of a higher reliability of the results obtained, because estimates on the value of ecosystem services are known to be highly uncertain (see, for example, ranges reported by Costanza et al. (1997). Also, none of the mentioned sophisticated studies integrated uncertainty into their analyses. An example how to integrate carbon storage as an ecosystem service in optimized tropical land-use allocation under the risk of fluctuating product prices has been provided by Knoke et al. (2013). However, a focus on mountain forest management combined with a sophisticated modelling of survival and price risks has been lacking in the studies discussed.

Of course, there are many alternatives to integrate multiple ecosystem services into optimization (see Uhde et al. 2015 for an overview). However, these options, for example Goal Programming (Tamiz und Jones 1998), may become quite complex when considering multiple forest stands under risk simultaneously. Still, there is ample opportunity to develop further the optimized forest management under multiple objectives. An ultimate advantage of the quantitative programming approaches over the so far often scenario based approaches to include ecosystem services is certainly that strategies result from well-defined objective functions and constraints. The resulting scenarios may, hence, be defended well in public discussions. Also, it is possible to revise optimizations, when stakeholders mention new expectations.

## 4.4 Austrian case study area

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.

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.

Our results for the A1B scenario show an increase share of hardwood within the chosen management options for the ingrowth. That means, under climate change conditions the admixing of hardwoods to softwood stands should be emphasized to count for the changing growth conditions in the Austrian CSA. Although that effect is primarily based on simulated changes in growth, 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.

## 4.5 Slovakian case study area

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 online supplement). 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.

## 4.6 General conclusions

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-risk stands 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 suggests 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 of a changing climate 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

The study presented here is part of the project “ARANGE - Advanced multifunctional forest management in European mountain ranges” (FP7-KBBE-2011-5) is funded by the European Commission, Seventh Framework Program under grant agreement number 289437. The authors wish to thank John Jacobs for the language editing of the manuscript.

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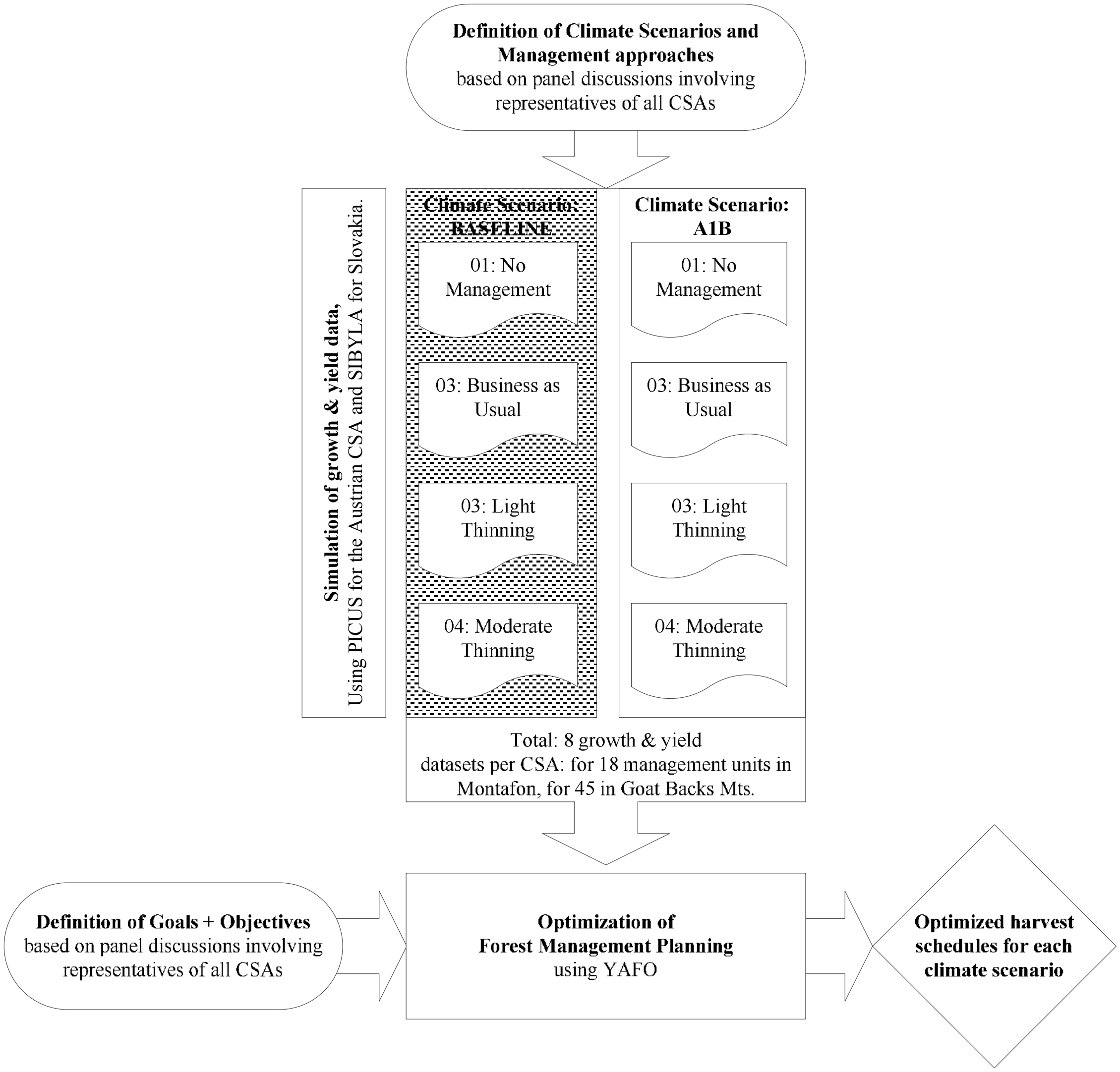
**Table 1: Financial results of the Montafon CSA. Net present value, standard deviation (STD), standard deviation relative to the NPV (variation coefficient VC), Value at risk (the value of the objective function), annuity and standard deviation of the annuity.**

| | **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 |
| A1B | 1,127 | 661 | *59%* | -411 | 24 | 14 |
| A1B VolMin 250 | 467 | 580 | *124%* | -881 | 10 | 12 |

**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 |



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

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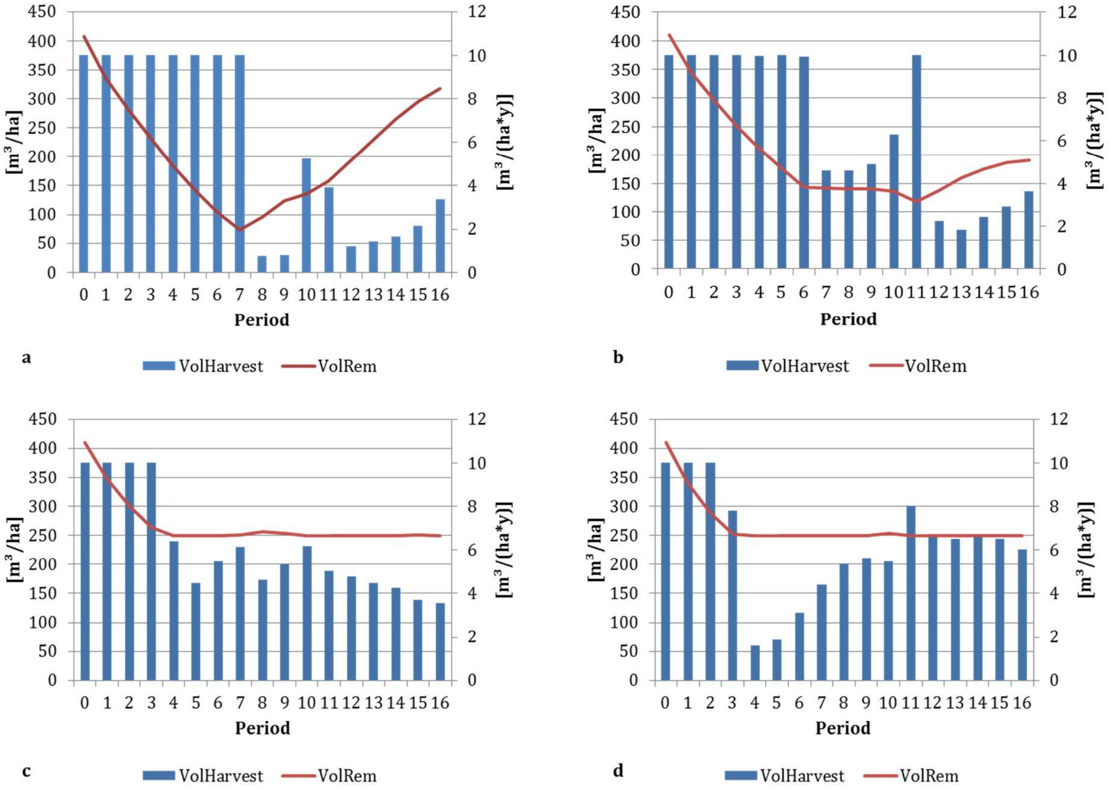

**Figure 2: Development of the growing stock (VolRem) and the timber amounts harvested (VolHarvest). Results from the Austrian CSA. a: BL scenario. b: A1B scenario. c: BL scenario, where additionally a minimum stocking volume of 250 m$^3$/ha is required. d: A1B scenario with the same minimum stocking volume required**

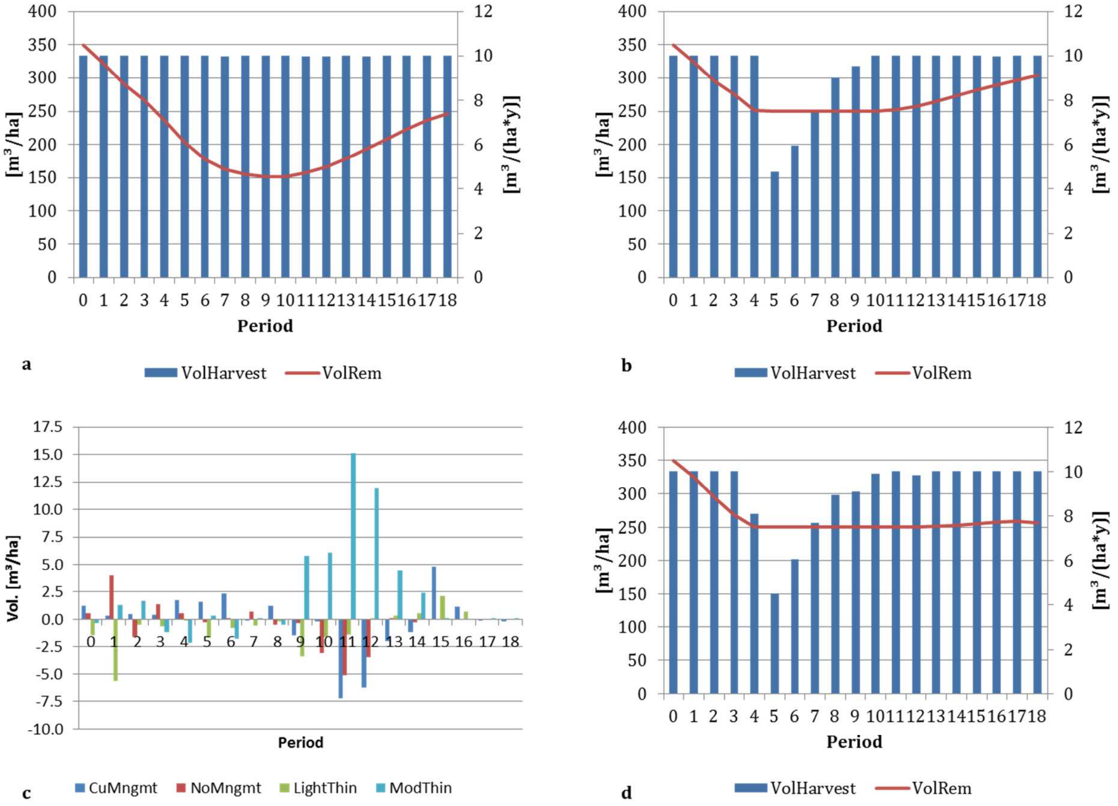

**Figure 3: Development of the growing stock (VolRem) and the amounts harvested (VolHarvest). Results from the Slovakian CSA. a: BL scenario. b: BL scenario, where additionally a minimum stocking volume of 250 m³/ha is required. c: Difference of the amounts harvested between the climate change scenario and the baseline scenario: a positive value means more harvests under climate change conditions. "CuMngmt": current management (BAU). "NoMngmt": no management. "LightThin": light thinning. "ModThin": a moderate close-to-nature thinning. d: A1B scenario, where additionally a minimum stocking volume of 250 m³/ha is required**