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Long-term impacts of increased timber harvests on ecosystem services and biodiversity: a scenario study based on national forest inventory data

Abstract

The transition to a climate-neutral economy is expected to increase future timber demands and endanger the multifunctionality of forests. National scenario analyses are needed to determine long-term forest management impacts and support forest policy making in defining guidelines for the sustainable provision of forests' ecosystem services and biodiversity (ESB). Using national forestry inventory data, the forest management model MASSIMO and a model to estimate harvesting costs, we simulated forest development in Switzerland under five politically relevant timber harvesting scenarios until 2106 (business as usual and four increased timber mobilisation scenarios). Model results were analysed using a utility-based multi-criteria approach regarding timber production, protection against gravitational hazards, carbon sequestration and biodiversity conservation for the whole of Switzerland and for five sub-regions. The development of ESB benefits over time and existing trade-offs were analysed. Apart from the Plateau region, the business-as-usual scenario resulted in the highest overall ESB benefits. However, this scenario did not mobilise possible timber potential, which is not in line with current forest policies. In the Plateau region, ESB benefited most under a constant growing stock scenario that guaranteed long-term sustainable timber usage. Nevertheless, both scenarios showed strong trade-offs between biodiversity conservation and the service carbon sequestration. The latter was achieved best under a scenario with conifer promotion and increased harvested timber volumes that can be used for long-living timber products and substitution of energy intensive materials and fossil fuels. Even though weighting the ESB according to regional management priorities further increased the trade-off situation, it also increased the overall benefits of harvesting scenarios, except for in mountainous regions. We conclude that no single scenario can maximize all ESB benefits simultaneously. A combination of locally adapted scenarios with targeted priorities can guarantee a higher degree of multifunctionality and long-term timber supply, but at the cost of locally more accentuated trade-offs. Overall, our study provides new insights into ESB interactions, and the presented multi-criteria framework and results provide a valuable basis to support forest policy decision making in Switzerland and beyond.

Keywords

biodiversity conservation, carbon sequestration, decision support, forest management, multi-criteria analysis, protection forest

Highlights

- Timber mobilisation scenarios were simulated using a NFI-based forest growth model
- Scenarios were analysed for ecosystem service benefits and trade-offs
- Benefits were assessed using indicator weights based on stakeholder opinion
- Increased harvests resulted in trade-offs between carbon storage and biodiversity
- Results have the potential to support decision making for Swiss forest policies

1 Introduction

The transition to a climate-neutral economy before the second half of this century is one of the main targets in Europe to mitigate the effects of climate change (European Commission, 2018). Forests play a crucial role in achieving this ambitious target as they provide a major sink for the climate-relevant greenhouse gas carbon dioxide. Additionally, the potential for the carbon sequestration of forest products and the substitution of CO_2-intensive material and energies by wood is widely accepted and accounted for under the Land Use, Land Use Change and Forestry LULUCF regulation (EU, 2018; Nabuurs et al., 2018; Werner et al., 2010). The climate-neutral view of forest products is expected to increase the demand for timber and other woody biomass to replace fossil-based energies and non-timber products (Ferranti, 2014; Hetemäki et al., 2017; Thees et al., 2017). However, increased demands for biomass were found to trade off with other important forest management objectives, such as the regulation of water and carbon cycles, the cultural service of recreation, the provision of protection against hazards and the conservation of biodiversity (Blattert et al., 2018; Gutsch et al., 2018; Lafond et al., 2017; Langner et al., 2017; Mina et al., 2017). Nevertheless, to maximize benefits for the whole of society, and to account for economic, ecological and social aspects of sustainable forest management, all relevant ecosystem services and biodiversity (ESB) need to be considered (MEA, 2005).

Several forest policies in Europe, therefore, aim to guide the sustainable management of finite forest resources to best meet multiple objectives in the long-term (EASAC, 2017). Nevertheless, harmonizing timber and non-timber demands and avoiding trade-offs is a challenging task for forest policy makers, as long-term policy impacts are difficult to foresee. Forest policy decision making can be supported by scenario analyses that illustrate forest management and its effects on ESB over long-term periods and from regional to national scales (Hoogstra-Klein et al., 2017). To that end, analyses based on data from national forest inventories (NFI) can be particularly relevant because they represent the whole forest area of a country. Recent examples of such large-scale studies include Jandl et al. (2018) that assessed the effects of climate-smart forest policies on biomass production and carbon sequestration in Austrian forests, and Gutsch et al. (2018) that investigated trade-offs between increased biomass production and biodiversity, water regulation and carbon sequestration objectives in German forests. However, none of these national studies accounted for ex-situ carbon storages in wood products and substitution aspects, which are essential for the comprehensive evaluation of forest management scenarios in terms of climate-change mitigation (Leskinen et al., 2018; Schmid et al., 2006; Werner et al., 2005). Moreover, none of these studies took into account harvesting costs in predicting future biomass availability. Harvesting costs strongly affect the amount of timber that can be mobilized, particularly in mountainous areas, where difficult terrain and limited accessibility lead to unprofitable timber harvests and increase the share of unmanaged mountain forests (Lexer and Bugmann, 2017;

Thees and Schmid, 2015). Unprofitable timber harvests reduce the available biomass potential of ex-situ carbon storage and substitution effects. Further, unmanaged forests trade-off with the protection service of forests against gravitational hazard, which is an important service in many densely populated mountainous regions in central Europe in the protection of settlements and traffic networks (Moos et al., 2018). Protection forests require the management of a resistant and resilient stand structure to provide an optimal long-term protection effect (Brang et al., 2008; Frehner et al., 2007). We thus hypothesise that, without considering aspects of ex-situ carbon storages and harvesting costs, national scenario analyses do not fully represent forestry’s contribution to climate-change mitigation. Additionally, no holistic analysis of scenario effects on ESB or related trade-offs among them are possible. Closing this research gap is necessary given that the results of national scenario analyses may otherwise lead to inaccurate policy decisions.

To assess holistic and complex interactions between multiple objectives, multi-criteria decision analysis (MCDA) methods have gained considerable importance in forest management (e.g., Ananda and Herath (2009); Myllyviita et al. (2011); Uhde et al. (2015)). In combination with forest growth models for long-term scenario simulations, MCDA is particularly suitable to illustrate synergies and trade-offs between multiple objectives (Wolfslehner and Seidl, 2010). In order to measure the effects of management on landscape ecosystem service multifunctionality, Manning et al. (2018) recently presented a conceptual MCDA framework related to the additive utility theory (multi-attribute value theory MAVT). However, to our knowledge, no previous study has analysed the effects of forest management scenarios on the provision of ESB at the national scale with such a framework (Blattert et al., 2018; Briceño-Elizondo et al., 2008; Diaz-Balteiro et al., 2017; Fürstenau et al., 2007; Langner et al., 2017; Schwenk et al., 2012). The applicability and usefulness of this method for large-scale forest ecosystem analyses is thus still an open research question. However, the concept is seen as a promising approach to reveal the complex interactions between multiple objectives in a transparent way, which is, in turn, essential for decision support in forest policy making.

As a case study, we used Switzerland because this European country represents several challenges for forest policy. Due to its dense population, topography and fragmented landscape, there are high demands for multiple forest objectives on a small scale. Furthermore, Switzerland has both easily accessible and productive forest areas for biomass production at low elevations as well as cost-intensive harvesting areas in mountainous regions, where protection against gravitation hazards is often the most important management objective (Huber et al., 2015). National-scale scenario analysis in Switzerland to date has focused mainly on timber production and carbon sequestration (Thürig and Kaufmann, 2010), and accounted for other objectives only implicitly (Stadelmann et al., 2016; Taverna et al., 2016). Holistic scenario effects on ESB have only been considered at scales of single forest stands, case study landscapes or small regions (Blattert et al., 2018; Elkin et al., 2013; Mina et al., 2017;

Temperli et al., 2017a; Temperli et al., 2017b). A nationwide and multi-objective investigation of future ESB provision does not yet exist for Switzerland.

The goal of this study was to quantify the overall benefits of ESB provision and the associated trade-offs that occur under politically-relevant long-term timber harvesting scenarios. The research questions were: i) How do forest ESB develop under different politically-relevant harvesting scenarios in Switzerland and its regions, particularly if ex-situ carbon storages and harvesting costs are also accounted for? ii) Are there trade-offs among ESB under the various scenarios? iii) How do overall ESB benefits relate to overall trade-offs?

To address these questions, we applied a utility-based indicator framework to assess the conservation of forest biodiversity and key ecosystem services provided by Swiss Forests, namely, the provisioning services timber protection and protection against gravitational hazards and the regulating service climate-change mitigation (BAFU, 2012, 2013). ESB were assessed with indicators that measure forest structural attributes simulated by the empirical forest growth simulator MASSIMO (Stadelmann et al., 2019), which is based on the Swiss NFI.

2 Material and methods

2.1 Study area and data

Forests cover 32% (1.32 Mio. ha) of Switzerland’s land mass and are monitored by the Swiss NFI on a regular national 1.4 km grid. The country can be divided into five production regions with similar forest growth conditions: the Jura, the Plateau, the Pre-Alps, the Alps and the Southern Alps (Figure 1) (Brändli, 2010; Brändli and Hägeli, 2019). In the Jura, the Plateau and the Pre-Alps, 60% of the forest area is covered by conifer forests (mainly Spruce, *Picea abies* L.). Changes in management paradigms aim to increase the potential natural vegetation in these regions, which is dominated by beech (*Fagus sylvatica* L.) and silver fir (*Abies alba* M.) towards higher elevations. Montane mixed spruce and fir forests and subalpine spruce forests prevail on the northern slope of the Alps. Stone pine- (*Pinus cembra* L.) larch (*Larix decidua* M.) forests form the high-elevation tree-line and Scotts pine (*Pinus silvestris* L.) and mountain pine (*Pinus mugo* T.) forests are common at the bottom and on the slopes of the central Alpine valleys, respectively. Mixed deciduous forests dominate the lower elevations on the southern slope of the Alps (Brändli, 2010). This study builds on the data of the second (NFI2: 1993–1995) and third Swiss NFI (NFI3: 2004–2006) resulting in a common grid of 5,086 sample plots in the productive forests (Figure 1). Further, we used data of the first half of the fourth NFI (NFI4b 2009-2013) for the definition of management scenarios. Sample plots consist of two concentric circles of 200 m^2 and 500 m^2 with calliper thresholds of 12 cm on the inner and 36 cm on the outer circle. Saplings and trees of < 12 cm DBH and ≥ 10 cm in height are measured on two 14 m^2 satellite plots, and dead logs and branches on the ground of > 7 cm in diameter are recorded on three transects.

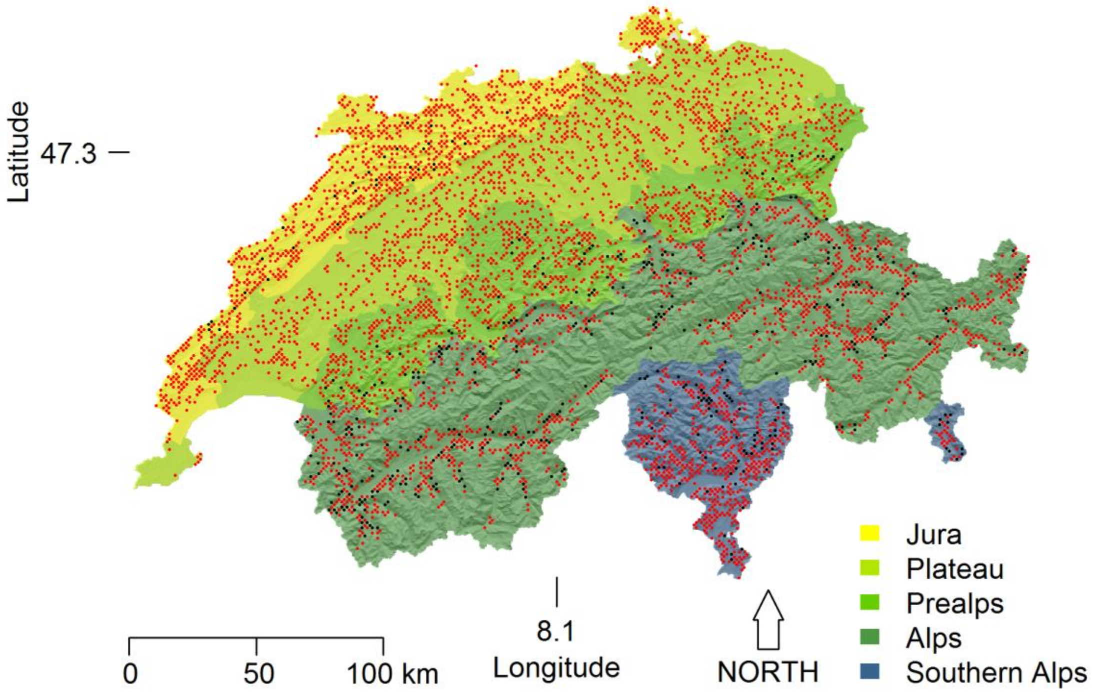

Figure 1: Location of the 5,086 NFI sample plots in Switzerland (red and black dots) and the five production regions (Jura, Plateau, Pre-Alps, Alps, Southern Alps) used as data in this study. Sample plots in black are located within the SilvaProtect perimeter for forests that protect against avalanches and rockfall (Losey and Wehrli, 2013). Note that this perimeter does not include protection forests against landslides.

2.2 Modelling forest development

Forest development in the sample plots of the Swiss NFI was simulated with the empirical individual-tree model MASSIMO (*Management Scenario Simulation MOdel*) (Stadelmann et al., 2019). We applied the scenarios presented by Stadelmann et al. (2016) to assess ESB provision nationwide and in the five production regions (Figure 1). MASSIMO projects growth, regeneration, mortality and management of individual trees in ten-year time steps. Density-dependent (self-thinning) and windthrow-induced mortality is simulated based on observed probabilities (Thürig et al., 2005). The simulation of forest management with MASSIMO comprises shelterwood cutting, thinning and regulating the conifer proportion in the regeneration. An assortment routine assigns harvested timber volumes to marketable timber products. By linking the harvest productivity model HeProMo, harvesting costs can be calculated (Frutig et al., 2009) (Appendix S3). Together with current market prices, this enables the assessment of potential harvest net revenues (Appendix S4).

2.3 Management scenarios

Forest development was simulated over 100 years (2006-2106) under five management scenarios representing potential future timber harvesting strategies. The scenarios were developed by Stadelmann et al. (2016) together with a group of experts representing stakeholders from policy, forest practice, the timber industry and from forest science. Overall, the scenarios aim to reflect current important forest trends in Switzerland as follows:

1) *Constant:* The baseline scenario keeps growing stock in all regions at the level observed in 2013 (NFI4b). The sum of all removals (harvests and mortality) corresponds to the timber volume increment.
2) *Business as usual (BAU):* The amount of harvesting is kept constant at the level observed between NFI3 and NFI4b illustrating the long-term effects of current management. This means increasing growing stocks throughout Switzerland except for the Plateau region where currently harvests exceed increments.
3) *Increment:* This scenario increases the long-term increment by reducing current growing stocks while keeping losses in growth small over the short- and medium-term. To this end, growing stock is reduced to 300 m^3 ha^{-1} until the year 2046 and left constant thereafter.
4) *Conifers:* This scenario meets rising demand for coniferous timber in Switzerland. Growing stocks are reduced to 300 m^3 ha^{-1} until 2046 and then increase again to 300-330 m^3 ha^{-1} depending on production region by respectively shorting and lengthening the rotation length and cutting cycles. To increase the production of conifer timber in the long-term, the proportion of conifer tree species is increased in the regeneration.
5) *Energy:* This scenario maximizes timber production meeting increasing demand for energy wood and wood-based chemicals, regardless of the target diameter. Growing stock is reduced until 2046 to 200 m^3 ha^{-1} in the Plateau, 250 m^3 ha^{-1} in the Jura, Pre-Alps, Valais and Southern Alps and 300 m^3 ha^{-1} in the Alps without Valais, then a constant growing stock is simulated. This rapid reduction in growing stocks and the shortening of the rotation period increase increment and usage. To compensate for the intensive management, forest reserves are established on rare forest locations and at locations where timber production is not very profitable.

Disturbances due to storms were simulated in all scenarios with a periodicity of 15 years. Whether storm damage occurs during a decade, where it occurs and how large it is (number of affected sample plots) is determined stochastically in MASSIMO (Thürig et al., 2005). For details, see Appendix S1.

2.4 Value-based indicator framework

2.4.1 Ecosystem service and biodiversity indicators

Management scenarios were analysed using 11 indicators that capture aspects of biodiversity and the key ecosystem services in Swiss forests (timber production, carbon sequestration and protection against avalanche and rockfall). The indicators were adapted from Blattert et al. (2017) (Table 1) and selected to first comply with the indicator frameworks from the Swiss federal office for the environment and cantonal forest services (Bernasconi et al., 2014). A second criterion was the available data from MASSIMO simulations, which included forest structural attributes (i.e. tree diameter at 1.3m (diameter at breast height - DBH), tree species, annual ingrowth and harvest).

Biodiversity conservation was assessed by species diversity measured with the Shannon index (Shannon and Weaver, 1949) and DBH diversity was measured with the Post-hoc index (Staudhammer and LeMay (2001), with DBH classes of 4 cm). For both indices, gamma diversity was calculated according to Jost (2007), representing diversity over all NFI sample plots in a region or in Switzerland. Furthermore, the number of habitat trees (large living trees with DBH > 80 cm) and the volume of deadwood (from mortality and harvesting residues) were assessed. Deadwood volume at the beginning of the simulations was summed from observed lying and standing deadwood. Exponential decay functions were used to account for deadwood decomposition (Appendix S2.2). Overall, the indicators represent an indirect measurement of forests structural diversity and habitat quality for diverse flora and fauna (Kraus and Krumm, 2013; Schall et al., 2017).

Timber production was assessed with the indicators annual harvested timber volume, annual volume increment, growing stock, and the harvested net revenue, which was calculated from timber revenues and harvesting costs (cf. Section 2.2, Appendix S3). Timber revenues were calculated from simulated volumes in harvested timber assortments to which we assigned currently recommended Swiss timber prices (Appendix S4).

Carbon sequestration was measured as the change in carbon pools relative to the beginning of the simulations (cf. Blattert et al. (2018)). Carbon pools included the change in above and below ground biomass of living trees and deadwood, taking into account the emissions caused by harvests or wind disturbances (in-situ storage). Additionally, we accounted for carbon storages in harvested wood products (HWP) and the substitution of non-timber products and fossil fuels, also defined as ex-situ storage. For the HWP we defined four life-span classes: long-, medium- and short-lived products and wood used for energy. The life span corresponds to an exponential decomposition with which the organic carbon bound in wood is released into the atmosphere (Wördehoff, 2016; Wördehoff et al., 2011). The substitution of energy-intensive products like steel or cement through timber leads to a decreased usage of fossil fuels during their production. These effects were calculated on the assumption that one m^3 of harvested timber saves the release of a certain amount of CO_2 to the atmosphere. Similar, the direct substitution of fossil fuels with timber, was calculated, which is considered as CO_2 neutral throughout its life cycle (Taverna et al., 2007). The detailed calculations are described in Appendix S2.

The protection service was assessed by an avalanche protection index (API) and a rockfall protection index (RPI) (Bugmann et al., 2017). The API indicates the ability of a forest stand to prevent avalanche releases. API calculations assume that for a given mean DBH, the protection ability of a stand can be quantified as the ratio between the observed basal area and a reference basal area above which avalanche release is impossible. Co-determinants are slope angle and the conifer-broadleaf ratio. The RPI quantifies the risk that a rock passes through a stand as the ratio of the maximal energy developed by the rock and the energy dissipated by the current forest stand. The required stand structural variables are the number of stems per hectare, the quadratic mean diameter of stems, the basal area per hectare and the basal area ratio of conifers to broadleaves. Additional variables include slope angle and the following, for which we assumed the mid-range values in parentheses suggested by Cordonnier et al. (2013): rock density (2,800 kg/m^3), rock volume (1 m^3), the initial fall height of the rock (20 m) and the length of the forested slope (250 m). The RPI is sensitive to these assumptions, which we accepted because the absolute values in the individual sample plots were less relevant for our study than the relative effect of management. The API and RPI values range between 0 and 1 (with 1 = optimal protection). Both indices were only calculated for NFI plots that are within the protection perimeters for avalanches and rockfalls according to SilvaProtect (Losey and Wehrli, 2013) (Figure 1).

2.4.2 Aggregation of indicators

Apart from the gamma diversities, the simulated variables habitat trees, deadwood, timber volume harvested, timber volume increment, growing stock, timber assortments and harvesting costs were averaged over sample plots to obtain estimates at regional and national levels. Carbon pools were calculated from regional or national averages of simulated growing stock, deadwood and harvested timber volumes, which were transferred into carbon equivalents. Accounting for the left skewed distribution of both API and RPI, we obtained aggregated values across the avalanche and rockfall protection forest perimeters by calculating the percentage of sample plots with high protection efficacy (i.e., with RPI and API values > 0.95).

2.4.3 Multi-criteria decision analysis

Management effects on ESB were analysed in ten-year time steps using MAVT (Ananda and Herath, 2009; Eisenführ et al., 2010; Kangas et al., 2015), an approach recently recommended for measuring landscape ecosystem service multifunctionality (Manning et al., 2018). MAVT is based on utility theory that assigns value functions to each indicator to represent the relationship between supply levels of ESB and the benefit it provides to humans. This normalises the indicator values and results in utility values of between 0 and 1 (with 1 = optimal indicator value) to allow comparison among ESB indicators. In this study, we used linear transformations as value functions (Equation 1) (Manning et al., 2018; van der Plas et al., 2016).

$$u(x_{i,j,k}) = \frac{x_{i,j,k} - min_k}{max_k - min_k}$$

Equation 1

where $u(x_{i,j,k})$ is the normalised indicator value at time (i) under strategy (j) in region (k), $x_{i,j,k}$ the simulated indicator value, max_k the maximum, and min_k the minimum simulated indicator value over all simulation intervals and scenarios in region (k).

The normalised values were summarised to partial utility values at the level of individual ESB and as an overall utility, which describes the benefit of each scenario (Equation 2). The additive utility function thereby considers weights for indicators and ESB, which reflect the potential preferences of decision makers for a specific ESB.

$$overall\ utility_{i,j,k} = \sum_{a=1}^{m} \lambda_{a,k} \left(\sum_{b=1}^{n} \lambda_b \ u(x_{i,j,k}) \right)$$

Equation 2

$$\sum_{b=1}^{n} \lambda_b = 1$$

$$\sum_{a=1}^{m} \lambda_{a,k} = 1$$

where λ_b are the weights for indicators for a specific ESB, and $\lambda_{a,k}$ are the weights for an ESB in region (k). Indicator weights were defined using the simple multi-attribute rating technique (SMART) (Kangas et al., 2015). Each indicator was given a rank according to its importance (high rank = important). The corresponding indicator weight is calculated by the individual rank divided by the ESB-specific cross sum of the assigned ranks. The definition of indicator-utility relationships (value functions) and indicator weights were supported by a stakeholder panel, which consisted of three representatives of forest policy-making (Federal Office for the Environment), two additional scientists (Swiss Federal Institute WSL) and the authors. During a workshop, we discussed the general importance of each indicator at the national scale and time horizon of this study.

Table 1: Selected indicators to describe ecosystem services and biodiversity (ESB), and indicator weights λ_b used in the additive utility function (Equation 2). Stakeholders representing Swiss forest policy-making and science defined the weights.

ESB	Indicator	Unit	Weight λ_b
Biodiversity conservation	Tree species diversity, Shannon index gamma	-	0.15
	Tree structural diversity, Post-hoc index gamma	-	0.15
	Deadwood volume	$m^3 ha^{-1}$	0.35
	Large living trees (habitat trees)	$n ha^{-1}$	0.35
Timber production	Growing stock	$m^3 ha^{-1}$	0.15
	Annual harvested timber volume	$m^3 ha^{-1} yr^{-1}$	0.30
	Annual volume increment	$m^3 ha^{-1} yr^{-1}$	0.15
	Harvest net revenue	$CHF ha^{-1} yr^{-1}$	0.40
Carbon sequestration	Average carbon change	$tC ha^{-1} yr^{-1}$	1.00
Protection against gravitational hazards	Rockfall protection index RPI	%	0.50
	Avalanche protection index API	%	0.50

We considered two variants of ESB weights in the additive utility function to investigate the sensitivity of ESB weights on overall benefits. In the first variant, ESB were given the same weight (equal preferences) in all regions (Table 2). In the second variant, we weighted ESB according to available information on the regional management priority (primary designated forest function). Forest area proportions on which timber production (TP) is prioritized was available from NFI surveys among forest managers. Priority areas for protection against gravitational hazards (PGH) were available from SilvaProtect perimeters for protection forest against rockfall and avalanches (Losey and Wehrli, 2013). Assuming that all forests in Switzerland (and not just the ca. 5% of the forest area in forest reserves and in the National park) support biodiversity and store carbon to some extent, we assigned half of the remaining weight after deducting TP and PGH to biodiversity conservation and carbon sequestration ((1 – weight_TP – weight_PGH) / 2) (Table 2).

Table 2: Weighting variants used in the additive utility function ($\lambda_{a,k}$) for ecosystem services and biodiversity (ESB) by region (BC = biodiversity conservation, TP = timber production, CS = carbon storage, PGH = protection against gravitational hazards).

ESB	Equal preference (weight $\lambda_{a,k}$)		Regional management priority (weight $\lambda_{a,k}$)					
	Plateau*	All other regions	Jura	Plateau	Pre-Alps	Alps	Southern Alps	Switzer-land
BC	0.33	0.25	0.135	0.10	0.24	0.34	0.37	0.245
TP	0.33	0.25	0.69	0.80	0.45	0.13	0.10	0.41
CS	0.33	0.25	0.135	0.10	0.24	0.34	0.37	0.245
PGH	0.00	0.25	0.04	0.00	0.07	0.19	0.14	0.10

* There are no NFI sample plots within the SilvaProtect perimeter for rockfall and avalanche protection in the Plateau region. Thus, a weight of zero for PGH was assigned for this region.

2.5 Trade-off analyses

Trade-offs between two individual ESB were illustrated by plotting the mean partial utilities over simulation time on a two-dimensional plot (Figure 4). The 1:1 line represents situations where equal benefits are provided for the provision of ESB1 and ESB2. Ideally, a scenario results in a high degree of benefit for both objectives (Bradford and D'Amato, 2012). However, scenarios may result in high benefit for some objectives and low benefit for others. This situation is referred to as a trade-off.

Overall trade-offs among ESB were quantified using the root mean square error (RMSE), which measures the spread away from the 1:1-line in a two-dimensional scatterplot of ESB pairs, as in Langner et al. (2017). The RMSE is based on the deviation of partial utilities for two management objectives (ESB1 - ESB2) at a certain time (i) as generated by a particular management scenario (j) in region (k), where (n) is the number of simulation intervals in which trade-off fluctuations are to be considered over the simulation time.

$$RMSE_{j,k} = \sqrt[2]{\frac{1}{n}\sum_{i=1}^{n}\left(ESB1_{i,j,k} - ESB2_{i,j,k}\right)^2} \qquad \textbf{Equation 3}$$

For any management scenario, the overall trade-off for a portfolio of ESB is calculated as the mean of all pairwise RMSE. For a portfolio of four ESB, six different ESB pairs can be defined.

The calculation of the RMSE was further extended to account for the effects of ESB weighting variants (Table 2) that were defined to quantify overall scenario benefits (Langner et al., 2017). Consequently, the partial utilities (U) in the matrix of (l) ESB were adjusted by the ratio of weight coefficients (a_w) from the management priority variant (GS_m) and the variant with equal weights for all ESB (GS_0).

$$U_{ESB(i,j,k,l,GS_m)} = U_{ESB(i,j,k,l,GS_0)} \frac{a_w\left(GS_{m(k)}\right)}{a_w\left(GS_{0(k)}\right)} \qquad \textbf{Equation 4}$$

Afterwards, the adjusted partial utilities for ESB were normalised to make the effects of the two weighting variants on trade-offs comparable. The min-max approach was applied to normalise the adjusted ESB utilities by using global minimum and maximum valued per region, similar to the standardisation on indicator level.

$$nU_{ESB(i,j,k,l,GS_m)} = \frac{\left(U_{ESB(i,j,k,l,GS_m)} - U_{ESB(min,k)}\right)}{\left(U_{ESB(max,k)} - U_{ESB(min,k)}\right)} \qquad \textbf{Equation 5}$$

The normalised matrix was finally used to calculate the deviations of ESB pairs and ultimately the overall RMSE (Equation 3). To illustrate the relationships between overall trade-offs and overall benefits of a scenario, both are jointly presented in one diagram.

3 Results

3.1 Development of ecosystem services and biodiversity

3.1.1 Timber production

Except from the Plateau, timber production was highest under *BAU* at the end of the simulation. Partial utilities increased to values between 0.64 (Jura) and 0.78 (Alps) (Figure 2). This is mainly because the increased growing stock (Appendix S5.1.1) was assigned a higher value by the min-max normalisation, and due to the stabilisation of harvest net revenues at an economically tolerable level (e.g., *BAU* stabilised net revenues in the Alps region around zero whereas all other scenarios received negative values, see Appendix S5.1.4). Harvesting costs are very high in Switzerland, particularly in mountainous terrains (Appendix S3), and due to the low harvesting intensity under *BAU* (Appendix S.51.2), these costs remained at a low level. However, under this scenario, necessary amounts of timber cannot be mobilized in the future. Harvesting costs also caused the drop in the indicator harvest net revenue under *Conifers* and *Energy*. Under these scenarios, timber assortments were mainly of small dimensions in the second half of the simulation period (Appendix S4), which are necessarily harvested at higher costs. Additionally, such dimensions achieve lower prices on timber markets, which further reduced net revenues.

In the Plateau region, timber production was most beneficial under *Conifers* and *Constant* with partial utilities reaching values of 0.54 and 0.52, respectively (Figure 2). Utilities under *Conifers* collapsed after the year 2046 and slowly recovered by the end of the simulation. In contrast, the results under *Constant* remained at the same level over the simulation period.

3.1.2 Carbon sequestration

Carbon sequestration was highest under *Conifers* in all regions, reaching partial utility values of 1.00 by 2106 (Figure 2). The second highest partial utility values were reached under *Energy* with values ranging between 0.21 (Jura) and 0.66 (Alps). The high values under *Conifers* can be explained by the higher timber harvest compared to *BAU*, under which carbon storages increased in long-living timber products and the substitution of non-timber products and fossil fuels. Lower partial utilities under *Energy* compared to *Conifers* were due to lower harvested timber amounts and the lower conifer proportion, which led to less timber usage in long-lived products.

Overall, partial utilities for carbon sequestration decreased from 2006 to 2106 in the Plateau region by 83% (*BAU)*, 100% (*Constant)* and 74% (*Increment*), as well as 25% in the Pre-Alps under *BAU* (Figure 2). However, this decrease resulted in an “overall” source of carbon only in the Plateau. All other scenarios and regions resulted in a carbon sink at the end of the simulation (Appendix S5.3).

The increased harvesting under *Conifers*, *Energy* and *Increment* reduced growing stocks and led to a carbon source in the living biomass (Figure 3). However, under all scenarios, except *BAU*, the drop in growing stock only slightly affected average annual carbon change. Carbon storage in timber products and substitution of fossil fuels and non-timber products compensated for this small effect.

3.1.3 Protection against avalanche and rockfall

The highest partial utilities for protection were projected for the Jura and the Pre-Alps under *Energy* with values of 0.33 and 0.44, respectively, at the end of the simulation (Figure 2). In contrast, under *BAU* the Alps (0.46), the Southern Alps (0.67) and the whole of Switzerland (0.49) had the highest values. The protection utilities for the protection forest perimeter throughout Switzerland increased by 4% by 2106 only under *BAU* while decreasing under all other scenarios (*Constant* -56%, *Increment* -67%, *Conifers* -47% and *Energy* -37%). Partial utilities for protection showed a humped development in almost all cases. These developments were controlled by the simulated increase in average DBH to which rockfall protection was positively and avalanche protection negatively related (cf. Appendix S5.4). A curvature in the development of both indices followed the unimodal development of the basal area, which was the result from MASSIMO-inherent routines for the simulation of protection forest management.

3.1.4 Biodiversity conservation

The highest partial utilities for biodiversity resulted under *BAU* (Figure 2) in all regions except for the Plateau. Values increased up to > 0.94 by the end of the simulation. The reason for this lies mainly in the low harvesting intensity (Appendix S5.1.2), which fostered deadwood accumulation (Appendix S5.2.3) and the number of large living trees per ha (Appendix S5.2.3). DBH diversity slightly increased partial utilities under *BAU*, mostly due to the increased abundance of larger trees (Appendix S5.2.4). Under the *Constant* scenario, biodiversity benefited most in the Plateau region (utility of 0.79 in 2106) because harvesting intensity was lowest under this scenario in this region.

Under the *Conifers* scenario, nearly constant (Jura > -7%) or decreasing (Plateau: -41%, Pre-Alps -63%, Alps -7%, Switzerland -20%) partial utilities were found for biodiversity. High harvesting activity under this scenario prevented the accumulation of deadwood and the retention of large living trees and reduced forest structural diversity. Further, species diversity decreased in response to the promotion of coniferous trees (Appendix S5.2.1). An exception was the Southern Alps region, where partial utilities increased slightly under *Conifers* because of the low harvest intensity in this region. Under the *Energy* scenario, in contrast, increasing partial utilities for biodiversity were found in all regions (> +82%), except for Pre-Alps where it decreased (-7%). The increase was caused by the established forest reserves under *Energy*, which led to a positive effect on structural and species diversity and large living trees (Appendix 5.2).

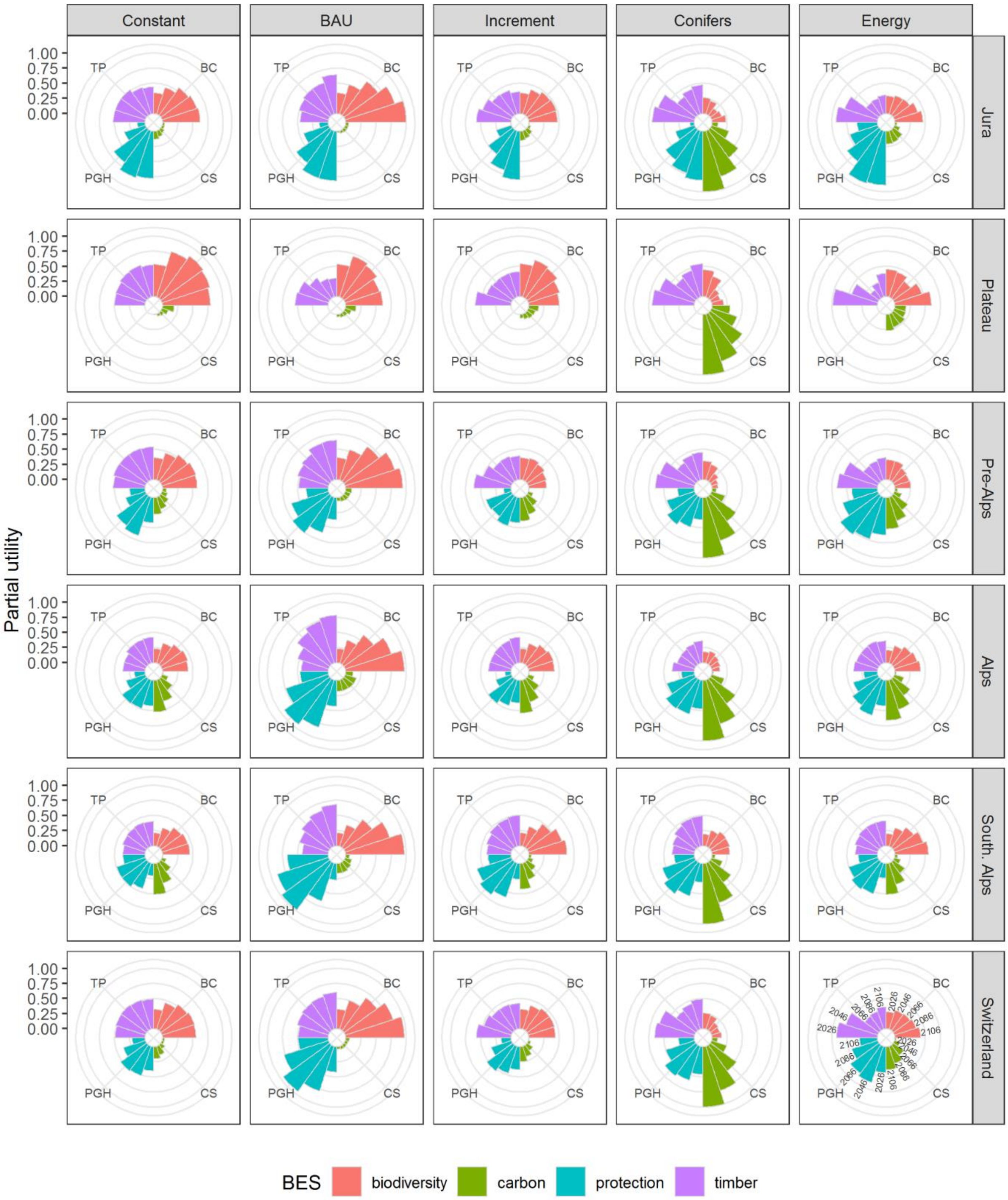

Figure 2: Partial utilities of ecosystem services and biodiversity (ESB) simulated under the five management scenarios at regional and national scales in Switzerland. Development over time is presented clockwise per ESB for the years 2026, 2046, 2066, 2086 and 2106 (legend shown for the region *Switzerland* and scenario *Energy,* bottom right).

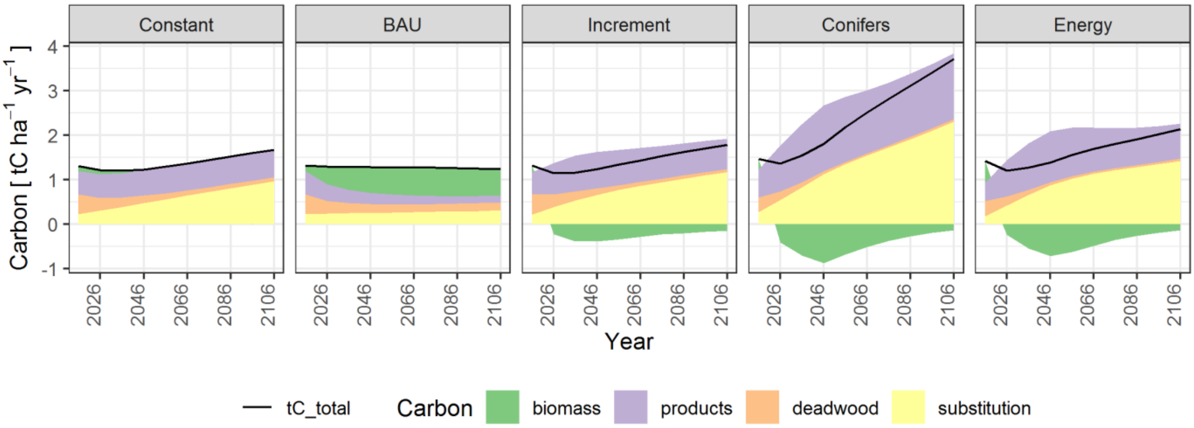

Figure 3: Development of the average annual carbon change in Switzerland under the five management scenarios. Changes in the total carbon pool (black line) and its corresponding compartments are shown: carbon stored in living tree biomass, in timber products and carbon stored in deadwood as well as the substitution of fossil fuels and of materials with an energy intensive production by woody biomass and products.

3.2 Trade-offs between individual ESB

Trade-offs between pairs of ESB varied greatly under the different scenarios (Figure 4). As the different regions showed quite similar developments (Appendix S8), we focus on the trade-offs for the whole of Switzerland.

All five scenarios showed small trade-offs between timber production and protection, while showing stronger effects for all other pairs of ESB. *Conifers* differed most from all other scenarios. It simultaneously promoted carbon, timber and protection. In contrast, it showed strong trade-offs between biodiversity in combination with all other paired services, meaning that all services benefited under the *Conifers* scenario, apart from biodiversity.

All other scenarios showed comparably low trade-offs between biodiversity conservation in combination with protection and timber. Under *BAU*, the greatest benefit resulted, with a high partial utility for each paired combination simultaneously (greater distance to the origin of the 1:1 line). However, trade-offs were found between carbon sequestration and all other objectives, which implies that all objectives profit from these scenarios with the exception of carbon sequestration. These trade-offs increased in the scenarios *Energy*, *Increment*, *Constant* and *BAU*.

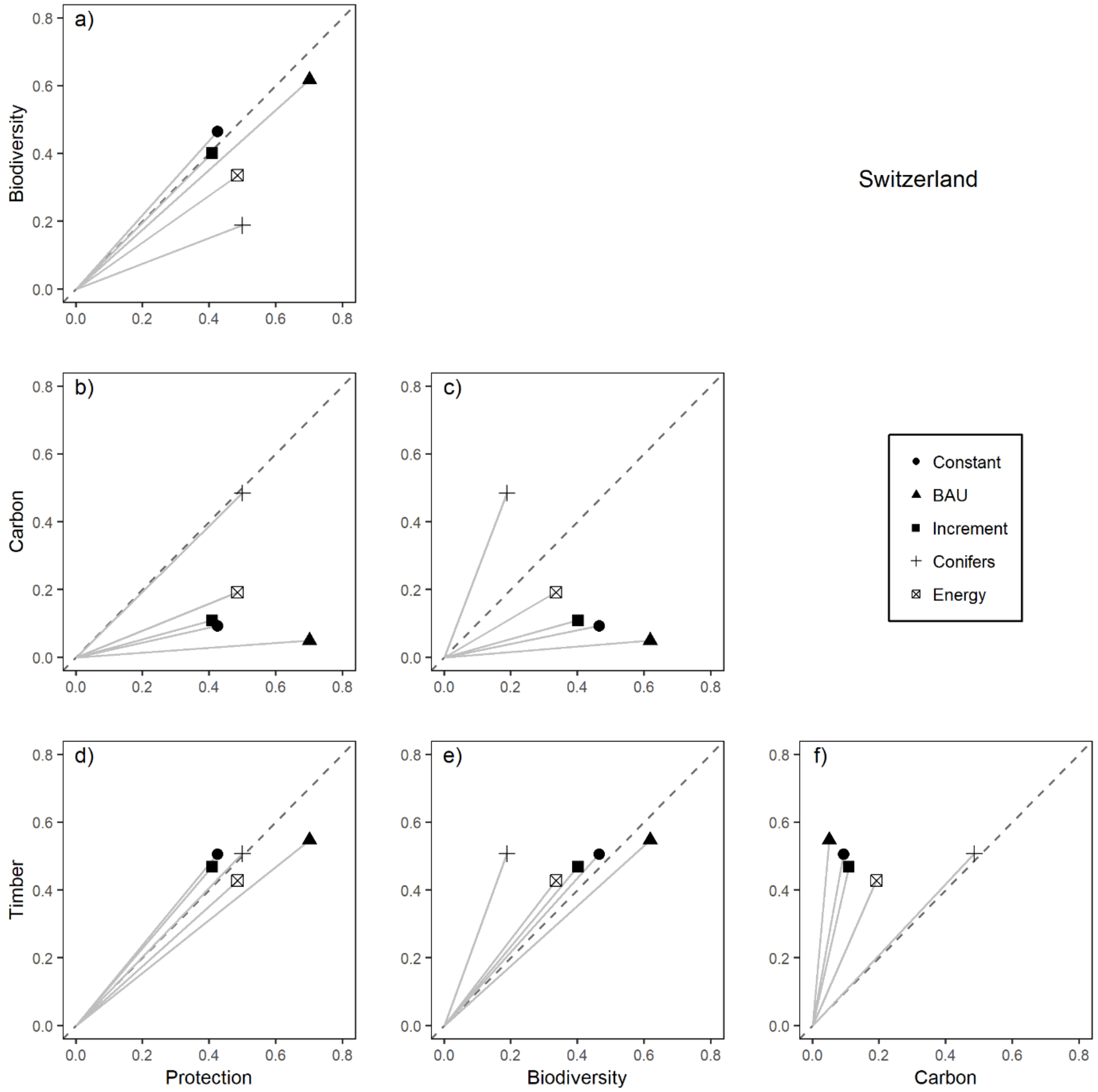

Figure 4: Scatter plots of paired management objectives illustrate the existence of trade-offs under the five management scenarios in Switzerland. Each scenario symbol represents the mean partial utility over the simulation period. The greater the distance between the scenario symbols and the 1:1 line, the greater the trade-off between ESB.

3.3 Overall benefits and trade-offs

3.3.1 Equal weights for ESB

The greatest mean overall benefits were found under the *BAU* scenario for the regions Jura (0.46), Pre-Alps (0.47), Alps (0.50), Southern Alps (0.47) and Switzerland (0.48) (Figure 5, Appendix S7). In the Plateau region, the highest overall benefits were reached under *Constant* (0.45) and *Conifers* (0.46). However, the benefits under *Constant* remained more stable (Appendix S7), whereas those under *Conifers* fluctuated over the simulation period following the changing harvesting intensity (Appendix S5.1.2). The lowest values were found in all regions under *Increment* and *Energy*, apart from the Southern Alps, where the lowest results occurred under *Constant*.

The scenarios with the highest benefits also exhibited the highest overall trade-offs. The *BAU* scenario had an overall trade-off that ranges between 0.06 (Jura) and 0.17 (Switzerland). The most beneficial scenarios for the Plateau region were *Constant* and *Conifers*, under which overall trade-off values of 0.08 and 0.05 were reached, respectively.

3.3.2 Management priorities for ESB

The weighting variant according to the primary management objective per region increased benefits, reaching the highest values in the Jura (+7% for *BAU*) and Plateau (+13% for *Constant* and *Conifers*) regions. In the Pre-Alps region, the value under *BAU* remained constant, while decreasing in the Alps (-8%), Southern Alps (-15%) and Switzerland (-4%).

The variant further resulted in trade-off values that were between four and seven times higher for those scenarios where the weighting variant had a positive effect on the overall benefits, namely in the Jura and Plateau, respectively. The variant thus simultaneously exacerbated the conflict between increasing overall benefits and pronounced trade-offs between ESB. In contrast, in the Alps and Southern Alps, where the goal preference decreased benefits, smaller increases of 16% (Alps) and 39% (Southern Alps) in the overall trade-offs were found.

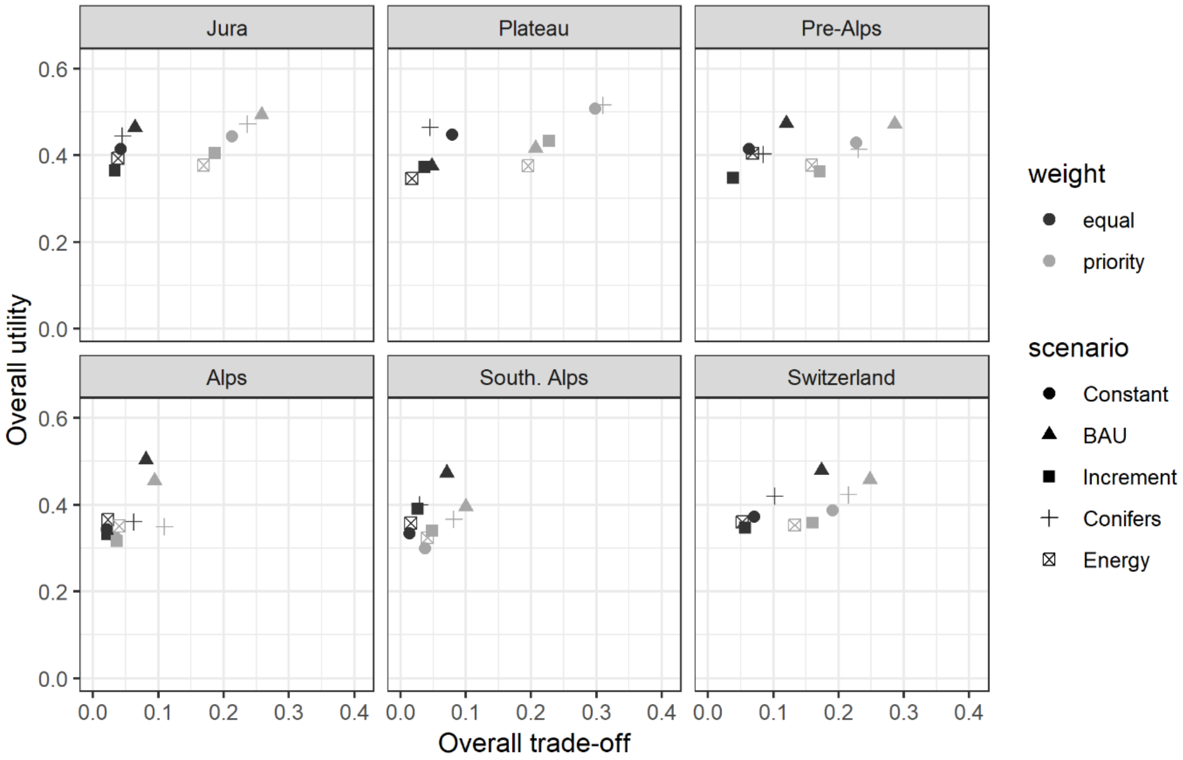

Figure 5: Mean overall utility (benefits) and overall trade-offs (measured by RMSE) under the five management scenarios and the two weighting variants (cf. Table 2) at regional and national scales in Switzerland.

4 Discussion and conclusion

In this study, an assessment framework that combines forest growth modelling and MCDA was applied to analyse developments of ESB in Swiss forests under politically relevant timber harvesting scenarios. The consideration of net revenues of harvested timber and ex-situ carbon storages in pools of harvested timber provide new insights on potential trade-offs between individual ESB. We answer the questions raised in the introduction by first discussing the effects of the scenarios on ESB provision. Secondly, we discuss potential trade-offs between ESB, emphasizing the effects of weights on ESB. We conclude by discussing the methodological aspects of the analysis framework, and by deriving implications for management.

4.1 Ecosystem services and biodiversity

4.1.1 Timber production

Timber production is usually assessed by the indicators harvested timber volume, increment and growing stock (Bugmann et al., 2017; Cordonnier et al., 2013). We additionally assessed harvested net revenues to account for potential future costs and income from timber harvests. Economic aspects were also considered in scenario analyses for ESB assessments by Fürstenau et al. (2007) and Seidl et al. (2007). However, both assessed the net present value (NPV) to rank alternative scenarios. The NPV approach is common to determine the value of forest resources and find an optimal investment strategy based on future monetary income and costs discounted to the present by using an interest rate (Klemperer, 1996). Instead, we used harvest net revenues, as in our view the optimal investment strategy is not important, but rather the potential future liquidity of the forest sector, which is expressed best by this indicator. In addition, net revenues are more intuitive and easier to interpret when applied to scenario analyses and, thus, easier to communicate with policy stakeholders. Further, the partial utilities for timber production would not change if NPV would be the indicator as presented in the appendix (S5.1.5).

Surprisingly, timber production was greatest for all regions under *BAU*, apart from the Plateau region where under *Constant* more benefit occurred (cf. section 3.1.1). In contrast, *Conifers* and *Energy* turned out to be unfavourable for timber production, despite the consideration of economic aspects in the additive utility function. This poor performance was caused by the decrease in growing stock and the high harvesting costs for smaller timber assortments in the second half of the simulation period which, in turn, resulted in negative net revenues. Our results differ from those of Fürstenau et al. (2007) and Seidl et al. (2007), who both recommended scenarios with increased harvesting intensities or an age class management and a shift to coniferous trees species for timber production. However, neither study accounted for assortment dimensions when calculating harvesting costs, nor did they investigate commercially unprofitable mountainous forest terrains. Additionally, Fürstenau et al. (2007) applied local value functions with a bell-shaped curve for growing stocks, which led to decreasing utility values for extensive or unmanaged forests with high growing stocks.

4.1.2 Carbon sequestration

Carbon sequestration and its sensitivity to forest management is of great interest in the context of climate-change mitigation (Bellassen and Luyssaert, 2014; Nabuurs et al., 2018). Forests can be structured through systematic interventions in such a way that their rate of CO_2 absorption increases (e.g., Thürig and Kaufmann (2010); Zanchi et al. (2014)). Additionally, it is important to account for carbon storage in wood products as well as the aspect of substitution to evaluate the contribution of forest management to the mitigation of greenhouse gases comprehensively (Nabuurs et al., 2017; Werner et al., 2010). For this study, we adapted the methodology for carbon assessment of Blattert et al. (2018) to account for such ex-situ carbon storages (cf. section 2.4.1).

The highest partial utilities for carbon were provided in all regions under *Conifers*. Mina et al. (2017) and Thürig and Kaufmann (2010) found the highest carbon sequestration rates under scenarios with extensive and no management. However, they did not take into consideration carbon storage due to wood products and substitution. Seidl et al. (2007) also showed that in-situ carbon storage is highest in unmanaged scenarios. Their scenarios with management, in contrast, stored substantial quantities of carbon in wood products and generated substantial substitution potentials. Pukkala (2014) and Perez-Garcia et al. (2005) also mentioned the large effects of management on carbon sequestration when all pools (in-situ and ex-situ) were considered together.

Overall, it is important to note that our carbon sequestration estimations were accomplished for the purpose of comparing the performance of different scenarios, and should not be seen as a precise prediction. Future research is, in our opinion, necessary by integrating a cascade use of products in the analysis to account for the first and second lifetimes of timber products. Processing harvested wood in accordance with the principle of cascade use and keeping wood products in use as long as possible, can further optimize the contributions of the forestry and timber sector to mitigate climate change (Werner et al., 2010).

4.1.3 Protection against gravitational hazards

The protection service was provided Swiss-wide best under *BAU*, which led to high growing stocks. Similar results were found by Irauschek et al. (2017) and Mina et al. (2017) who assessed the protection service under varying management types with RPI and API in different case studies in the Alps. Both recommended a scenario with low harvesting intensity or no management. However, a management approach such as *BAU* leads to old growth forest structures with many large living trees (Appendix

S5.2.4), which in turn leads to forest conditions that are vulnerable to several disturbances (Bebi et al., 2017; Temperli et al., in review). In contrast, guaranteeing optimal protection in the long-term requires sufficient regeneration and younger trees to sustain a stable stand structure (Brang et al., 2008; Frehner et al., 2007).

A major difference, compared to other studies which used RPI and API, is that they all assessed the protection service of forest stands (Irauschek et al., 2017; Mina et al., 2017; Pardos et al., 2016), whereas we focused on NFI-plot levels. The RPI indicator is, however, based on the principles behind the tool RockforNet (Berger and Dorren, 2007; Dorren et al., 2015), which was developed to assess the protection efficacy of individual forest stands. Besides stand parameters, it also accounts for specific site conditions (potential rock size, fall height, forested slope length), which were not yet available at the NFI plot level. On these grounds, we followed the recommendations of Cordonnier et al. (2013). In contrast, the API does not account for canopy gaps due to management (Cordonnier et al., 2013), even though they are important for avalanche release (Frehner et al., 2007). Thus, the suitability of RPI and API to be applied to NFI plots may be limited. Consequently, the absolute values of both indices need to be interpreted with caution, and only the relative effect of management scenarios can be reliably assessed and interpreted.

4.1.4 Biodiversity conservation

Biodiversity objectives were provided best under *BAU* in all regions, apart from the Plateau, where the greatest benefits were found under *Constant* (Figure 2). The increasing (*BAU*) and stable (*Constant*) growing stocks under these scenarios fostered deadwood and large living trees, which are generally recognised as important habitat attributes for taxa (birds, mammals, fungi and insects) that depend on old-growth forest features (Moning and Müller, 2009; Rosenvald et al., 2011).

Our results are in accordance with other MCDA studies that investigated biodiversity aspects under different management scenarios (Carpentier et al., 2016; Diaz-Balteiro et al., 2017; Mina et al., 2017). Many of these found scenarios with extensive or no management to be most beneficial for biodiversity. However, such studies only assessed indicators that measure structural attributes found in late successional stages (e.g., deadwood from mortality and habitat trees). We additionally assessed tree size and species diversity as did Langner et al. (2017). The deadwood pools in our simulations also included harvesting residues, which can also provide valuable biotopes for deadwood-dependent species (Lachat et al., 2014; Ranius et al., 2018). Our results predicted deadwood pools of greater than 50 m^3 per hectare for all scenarios Swiss-wide. However, these pools consisted mainly of fine wood litter under the *Conifer* and *Energy* scenarios, particularly in the Jura, Plateau and Pre-Alps (see Appendix S5.2.3). While such values comply with recommended target thresholds for biodiversity conservations (Müller and Bütler, 2010), they may also result from decay rates for fine woody litter that have little empirical basis, implying that there is a potential underestimation of litter decay. Hence, these deadwood pools need to be interpreted cautiously.

The highest gamma diversity of tree species was provided under *Energy* in Switzerland (Appendix S5.2.1). Accounting for residues in deadwood pools and gamma diversities increased the partial utilities for biodiversity in nearly all regions under *Energy*. The importance of regional gamma diversity for conservation and the positive effect of forest management on it have recently been noted by Schall et al. (2017). Additionally, Hilmers et al. (2018) highlighted the strong influence of forest succession on biodiversity, and emphasize the importance of early successional stages for high diversity, which usually follow final harvesting activities. They recommend that conservation strategies should aim at a more balanced representation of all successional stages (early and late) as this lead overall to higher habitat heterogeneity. Apart from management, disturbances can also have a positive effect on forest heterogeneity and thus on biodiversity (Thom et al., 2017). We did not consider this effect separately in our biodiversity assessments. Nevertheless, windthrow probabilities were included in all scenarios in the MASSIMO simulations (section 2.2).

4.2 Trade-offs arising from scenarios

While several studies have focused on synergies and trade-offs between ESB under different management scenarios (e.g., Lafond et al. (2017); Mina et al. (2017); Seidl et al. (2007)), and by using MCDA-methods (Langner et al., 2017), only a few studies have done so at national scales (Verkerk et al., 2014), and based on NFI data (Gutsch et al., 2018). We addressed these two aspects simultaneously, focusing on the relationship between key ESB in Swiss forests (BAFU, 2013). Thereby, we focused not only on trade-offs among paired objectives, but also accounted for overall trade-offs arising under the scenarios.

The scenarios with the highest ESB benefit per region showed simultaneously the highest overall trade-offs (Figure 5). Furthermore, weighting ESB according to regional management priorities increased the trade-off situation while also increasing the overall benefits of harvesting scenarios, apart from the mountainous region Alps and Southern Alps, where benefits decreased. A similar decreasing effect in mountainous areas was also reported by Langner et al. (2017), who investigated trade-offs in several European mountain case studies. Strong trade-offs were found between the carbon sequestration objective and all other objectives. In contrast, trade-offs were weak between biodiversity aims and the services timber production and protection (Figure 4). This result differs from most other studies that have investigated these objectives. For example, Mina et al. (2017) found synergy effects between carbon and biodiversity and protection under scenarios with extensive or no management. Synergies were also found between carbon sequestration and biodiversity (habitat) by Gutsch et al. (2018). However, both studies only accounted for in-situ carbon sequestrations (cf. Section 4.1.2). Further, most other studies have also identified trade-offs between timber production and biodiversity (e.g., Gutsch et al. (2018); Lafond et al. (2017); Mina et al. (2017)). However, these studies assessed timber production mainly by harvested timber volumes, whereas we also included economic aspects (cf. Section 3.1.1), which have a decisive influence on the economically sustainable amount of biomass that can be harvested. In contrast, this study is in line with others that also found a synergistic relationship or lack of trade-off between biodiversity and protection (Lafond et al., 2017; Mina et al., 2017).

Our decision to account for aspects such as ex-situ carbon sequestration and economic aspects thereby results in a considerably changed view of how politically-relevant scenarios for timber harvesting need to be analysed. Overall, the combined trade-off and benefit analysis have demonstrated that these aspects need to be considered jointly for a consistent evaluation of alternative management scenarios within the framework of sustainable forest management.

4.3 Analysis framework

The combined application of forest modelling and MCDA enabled the assessment of ESB provision under varying management scenarios. It made use of the simulation model MASSIMO that has been applied in several studies to assess carbon sinks and national greenhouse dynamics (Thürig and Kaufmann, 2010; Werner et al., 2010) and to evaluate various timber mobilization scenarios in Swiss forests (Stadelmann et al., 2016; Temperli et al., 2017a; Temperli et al., 2017b). However, our simulations did not account for climate change, which is expected to strongly affect forest ecosystems (Hanewinkel et al., 2013; Reyer et al., 2014) and the provision of ESB in the future, particularly under more extreme climate scenarios and at low-elevation (Mina et al., 2017; Pardos et al., 2016). Thus, climate-sensitive formulations of the main processes of growth (Rohner et al., 2018), regeneration (Zell et al., 2019) and mortality (Etzold et al., 2019) should be integrated into MASSIMO for future studies, in order to fully account for climate-change effects.

In combination with climate change, disturbances are expected to increasingly affect forest ecosystems (Seidl et al., 2020; Seidl et al., 2017). In Switzerland, windthrow and bark beetle outbreaks are particularly important. While considering windthrow probabilities in our simulations, we did not respect bark beetle outbreaks, which often occur along with wind disturbances, particularly in coniferous stands (Marini et al., 2017; Stadelmann et al., 2014; Temperli et al., 2013).

Considering climate change and bark beetle disturbances would likely increase the mortality of spruce in our simulations and lower timber harvests, particularly under the *Conifers* scenario. Thus, the high carbon sequestration effects of this scenario would decrease, in turn, diminishing trade-offs with biodiversity conservation. We therefore suggest that future investigations with MASSIMO need to consider the combined effects of climate change and disturbances on forest ecosystems.

The current set of management scenarios may be extended by adaptation scenarios that increase the resilience of forests against the uncertainty of cumulative global changes. Messier et al. (2019) advise to use the most efficient forest management and silvicultural practices and to manage forests as complex adaptive networks to increase the resistance and resilience capacity of forests. Close to nature management methods like single-tree selection, group selection and shelterwood, which are widely applied in Switzerland, are a promising approach to increase the adaptive capacity of forests, since it promotes structural diversity and tree resistance to stressors (Brang et al., 2014). Those methods can further be improved by increasing tree species richness, also by non-local provenances (Frank et al., 2017) or even non-native species (Brang et al., 2016). Non-native tree species currently recommended for Switzerland are Douglas fir (*Pseudotsuga menziesii*), large coastal fir (*Abies grandis*) and oriental beech (*Fagus orientalis*), if they are planted in mixture with native tree species and outside of forest communities of high conservation value (Brang et al., 2016). Especially, non-native coniferous tree-species can reduce the risks of climate change for ecosystem services like timber production and carbon sequestration and could be a valuable alternative to spruce within the *Conifers* scenario in the future.

The MAVT method has proven to be a good approach to provide information for decision making with regard to forest policy, and has shown high flexibility by respecting stakeholder preferences. The merits and robustness of this concept for measuring the multifunctionality of ecosystem services have recently been highlighted by Manning et al. (2018). In this study, we adapted the indicator framework of Blattert et al. (2017), which focused on the local forest management level, to the Swiss regional/national scale and matched it with the forest structural attributes simulated by MASSIMO. Structural attributes are good predictors for assessing ESB as well as their synergies and trade-offs (Felipe-Lucia et al., 2018). In addition, we replaced the local management-level value functions of Blattert et al. (2017) by min-max normalisations based on the simulated model output. The advantages of this approach are that: i) it avoids the difficult task of defining optimal target values for each indicator from the stakeholder-panel, ii) it adequately considers the specific forest situation in each region, and iii) it enables relative scenario comparisons by normalising indicators on an interval scale. The disadvantage of min-max normalisation is that is does not permit interpretations on the degree to which target or threshold values are reached, such as for biodiversity aspects (cf. Manning et al. (2018); van der Plas et al. (2016)). Further, no unimodal relationship can be considered between indicator outcome and expected utility value (cf. Fürstenau et al. (2007); Manning et al. (2018)). However, due to the focus on several indicators, regions and management scenarios and the long-term perspective, a relative scenario comparison is, in our view, a practicable and transparent approach for policy decision support.

The indicator and ESB weights have a distinctive impact on overall benefits and trade-offs (Fürstenau et al., 2007; Schwenk et al., 2012). Indicator weights were defined with a stakeholder-panel to ensure a representative view on indicator importance in Switzerland. We considered a weighting variant with regionally adapted primary forest functions, according to the NFI survey. Defining ESB weights, however, presented a difficulty in the large-scale application of MAVT, as no information was available regarding management priorities for biodiversity conservation (apart from the approximately 5% forest reserve area) and carbon sequestration at the NFI plot level. This is perhaps the reason why the only MCDA studies we are aware of have focused on small case studies or single forest stands (e.g., Blattert et al. (2018); Diaz-Balteiro et al. (2017); Langner et al. (2017)), where management priorities are often clearly defined. To illustrate the effect of weights, we compared the results with a baseline weighting variant, in which equal preferences were assigned to the objectives. Under both variants, the same scenarios reached the highest overall benefit, with slightly increasing or decreasing values (Figure 5). However, a distinctive effect was observed for overall trade-offs, particularly in the low elevation regions of Switzerland. We thus conclude that weighting scenarios must be supported as broadly as possible. If no information from the literature or existing data is available, weights should be defined by a well-balanced stakeholder group representing economic, ecological and social perspectives.

4.4 Implications for forest management

There is growing demand by decision-makers for research on the impact of policy strategies on ESB and human benefits. Consequently, building the bridge between ESB research and the information required in practice to support decisions is currently of high importance (Olander et al., 2017). The main objective of this study was to develop a holistic value-based analysis framework for analysing impacts of politically-relevant forest management scenarios on key ESB in Swiss forests, as well as identifying previously unknown trade-offs.

Our study indicates that, apart from the Plateau, current management practice in Switzerland (*BAU*) provides the highest ESB benefits. However, under *BAU*, possible timber potentials are not mobilised, which are highly recommended by the Swiss Forest Policy to foster the forestry and timber sector and to mitigate the effects of climate change (BAFU, 2013; BAFU et al., 2014). In the Plateau region, ESB benefits were highest under the constant growing stock scenario by additionally guaranteeing long-term and sustainable timber usage. Nevertheless, both management scenarios (*BAU*, *Constant*) showed a strong trade-off between biodiversity conservation and carbon sequestration. The latter service is achieved best under a scenario promoting coniferous timber utilisation (*Conifers*), which, in turn, provides wood for long-living construction materials and substitutes non-timber and energy intensive products. Considering regional management priorities strongly increased the overall trade-off situation, particularly in lowland regions. We thus conclude that no single management strategy is appropriate to maximize the provision of multiple ESB simultaneously. A targeted combination of forest stand management strategies with different dominant management objectives can lead to a higher degree of multifunctionality at the landscape level than one forest management practice (Lagergren and Jönsson, 2017). Such a segregation of the forest landscape offers a compromise by combining the positive aspects of several management scenarios to best achieve multiple forest policy objectives. This has been recommended by several studies (e.g., Blattert et al. (2018); Carpentier et al. (2016); Côté et al. (2010); Messier et al. (2009)). Nevertheless, management in order to support ESB should be evaluated carefully at the local (stand) scale, as the most advantageous scenario clearly depends on the specific needs of ESB (Mina et al., 2017). For example, protection against avalanches and rockfall cannot be balanced against other objectives in most cases, but is simply necessary to save lives.

Overall, the consideration of ex-situ carbon storages and accounting for harvesting cost in our scenario analyses had a strong impact on ESB development and on trade-offs, as demonstrated by our comparisons with other findings. In this way, our study provides new insights into ESB interactions. Our findings have the potential to optimise future forest management and maximise the sustainable provision of ESB benefits at regional and national scales, providing a valuable basis to support decision making for forest policies in Switzerland and beyond.

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