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

**Year:** 2020

**Version:** Accepted version (Final draft)

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**Please cite the original version:**

Blattert, C., Lemm, R., Thürig, E., Stadelmann, G., Brändli, U.-B., & Temperli, C. (2020). Long-term impacts of increased timber harvests on ecosystem services and biodiversity : A scenario study based on national forest inventory data. *Ecosystem Services*, 45, Article 101150. <https://doi.org/10.1016/j.ecoser.2020.101150>

# 1 Long-term impacts of increased timber harvests on 2 ecosystem services and biodiversity: a scenario study 3 based on national forest inventory data

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## 5 **Abstract**

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

31

## 32 **Keywords**

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

35

36 **Highlights**

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

42

## 43 **1 Introduction**

44 The transition to a climate-neutral economy before the second half of this century is one of the main  
45 targets in Europe to mitigate the effects of climate change (European Commission, 2018). Forests play  
46 a crucial role in achieving this ambitious target as they provide a major sink for the climate-relevant  
47 greenhouse gas carbon dioxide. Additionally, the potential for the carbon sequestration of forest  
48 products and the substitution of CO<sub>2</sub>-intensive material and energies by wood is widely accepted and  
49 accounted for under the Land Use, Land Use Change and Forestry LULUCF regulation (EU, 2018;  
50 Nabuurs et al., 2018; Werner et al., 2010). The climate-neutral view of forest products is expected to  
51 increase the demand for timber and other woody biomass to replace fossil-based energies and non-  
52 timber products (Ferranti, 2014; Hetemäki et al., 2017; Thees et al., 2017). However, increased  
53 demands for biomass were found to trade off with other important forest management objectives,  
54 such as the regulation of water and carbon cycles, the cultural service of recreation, the provision of  
55 protection against hazards and the conservation of biodiversity (Blattert et al., 2018; Gutsch et al.,  
56 2018; Lafond et al., 2017; Langner et al., 2017; Mina et al., 2017). Nevertheless, to maximize benefits  
57 for the whole of society, and to account for economic, ecological and social aspects of sustainable  
58 forest management, all relevant ecosystem services and biodiversity (ESB) need to be considered  
59 (MEA, 2005).

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

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

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

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

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

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

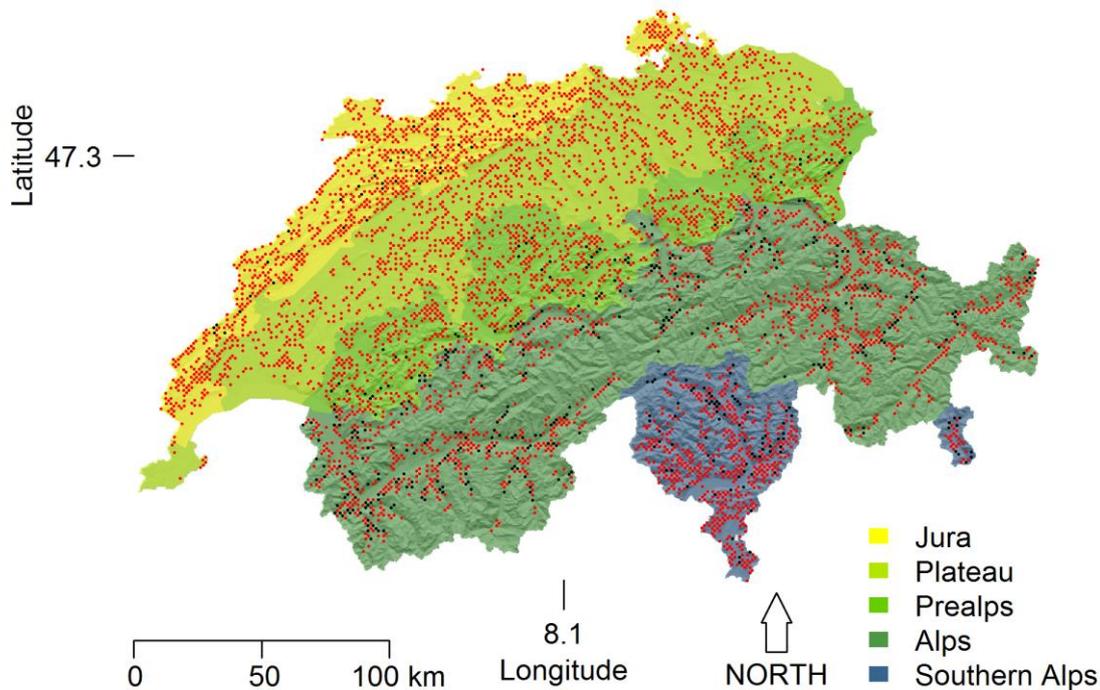
121 To address these questions, we applied a utility-based indicator framework to assess the conservation  
122 of forest biodiversity and key ecosystem services provided by Swiss Forests, namely, the provisioning  
123 services timber protection and protection against gravitational hazards and the regulating service  
124 climate-change mitigation (BAFU, 2012, 2013). ESB were assessed with indicators that measure forest  
125 structural attributes simulated by the empirical forest growth simulator MASSIMO (Stadelmann et al.,  
126 2019), which is based on the Swiss NFI.

## 127 **2 Material and methods**

### 128 **2.1 Study area and data**

129 Forests cover 32% (1.32 Mio. ha) of Switzerland's land mass and are monitored by the Swiss NFI on a  
130 regular national 1.4 km grid. The country can be divided into five production regions with similar forest  
131 growth conditions: the Jura, the Plateau, the Pre-Alps, the Alps and the Southern Alps (Figure 1)  
132 (Brändli, 2010; Brändli and Hägeli, 2019 ). In the Jura, the Plateau and the Pre-Alps, 60% of the forest  
133 area is covered by conifer forests (mainly Spruce, *Picea abies* L.). Changes in management paradigms  
134 aim to increase the potential natural vegetation in these regions, which is dominated by beech (*Fagus*  
135 *sylvatica* L.) and silver fir (*Abies alba* M.) towards higher elevations. Montane mixed spruce and fir  
136 forests and subalpine spruce forests prevail on the northern slope of the Alps. Stone pine- (*Pinus*  
137 *cembra* L.) larch (*Larix decidua* M.) forests form the high-elevation tree-line and Scotts pine (*Pinus*  
138 *silvestris* L.) and mountain pine (*Pinus mugo* T.) forests are common at the bottom and on the slopes  
139 of the central Alpine valleys, respectively. Mixed deciduous forests dominate the lower elevations on  
140 the southern slope of the Alps (Brändli, 2010). This study builds on the data of the second (NFI2: 1993–  
141 1995) and third Swiss NFI (NFI3: 2004–2006) resulting in a common grid of 5,086 sample plots in the  
142 productive forests (Figure 1). Further, we used data of the first half of the fourth NFI (NFI4b 2009-2013)  
143 for the definition of management scenarios. Sample plots consist of two concentric circles of 200 m<sup>2</sup>  
144 and 500 m<sup>2</sup> with calliper thresholds of 12 cm on the inner and 36 cm on the outer circle. Saplings and

145 trees of  $< 12$  cm DBH and  $\geq 10$  cm in height are measured on two  $14 \text{ m}^2$  satellite plots, and dead logs  
 146 and branches on the ground of  $> 7$  cm in diameter are recorded on three transects.



147  
 148 **Figure 1:** Location of the 5,086 NFI sample plots in Switzerland (red and black dots) and the five production regions (Jura,  
 149 Plateau, Pre-Alps, Alps, Southern Alps) used as data in this study. Sample plots in black are located within the SilvaProtect  
 150 perimeter for forests that protect against avalanches and rockfall (Losey and Wehrli, 2013). Note that this perimeter does  
 151 not include protection forests against landslides.  
 152

## 153 2.2 Modelling forest development

154 Forest development in the sample plots of the Swiss NFI was simulated with the empirical individual-  
 155 tree model MASSIMO (*Management Scenario Simulation MOdel*) (Stadelmann et al., 2019). We applied  
 156 the scenarios presented by Stadelmann et al. (2016) to assess ESB provision nationwide and in the five  
 157 production regions (Figure 1). MASSIMO projects growth, regeneration, mortality and management of  
 158 individual trees in ten-year time steps. Density-dependent (self-thinning) and windthrow-induced  
 159 mortality is simulated based on observed probabilities (Thürig et al., 2005). The simulation of forest  
 160 management with MASSIMO comprises shelterwood cutting, thinning and regulating the conifer  
 161 proportion in the regeneration. An assortment routine assigns harvested timber volumes to  
 162 marketable timber products. By linking the harvest productivity model HeProMo, harvesting costs can

163 be calculated (Frutig et al., 2009) (Appendix S3). Together with current market prices, this enables the  
 164 assessment of potential harvest net revenues (Appendix S4).

165

## 166 **2.3 Management scenarios**

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

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

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

198

## 199 **2.4 Value-based indicator framework**

### 200 **2.4.1 Ecosystem service and biodiversity indicators**

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

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

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

223 Carbon sequestration was measured as the change in carbon pools relative to the beginning of the  
224 simulations (cf. Blattert et al. (2018)). Carbon pools included the change in above and below ground  
225 biomass of living trees and deadwood, taking into account the emissions caused by harvests or wind  
226 disturbances (in-situ storage). Additionally, we accounted for carbon storages in harvested wood  
227 products (HWP) and the substitution of non-timber products and fossil fuels, also defined as ex-situ  
228 storage. For the HWP we defined four life-span classes: long-, medium- and short-lived products and  
229 wood used for energy. The life span corresponds to an exponential decomposition with which the  
230 organic carbon bound in wood is released into the atmosphere (Wördehoff, 2016; Wördehoff et al.,  
231 2011). The substitution of energy-intensive products like steel or cement through timber leads to a

232 decreased usage of fossil fuels during their production. These effects were calculated on the  
233 assumption that one m<sup>3</sup> of harvested timber saves the release of a certain amount of CO<sub>2</sub> to the  
234 atmosphere. Similar, the direct substitution of fossil fuels with timber, was calculated, which is  
235 considered as CO<sub>2</sub> neutral throughout its life cycle (Taverna et al., 2007). The detailed calculations are  
236 described in Appendix S2.

237 The protection service was assessed by an avalanche protection index (API) and a rockfall protection  
238 index (RPI) (Bugmann et al., 2017). The API indicates the ability of a forest stand to prevent avalanche  
239 releases. API calculations assume that for a given mean DBH, the protection ability of a stand can be  
240 quantified as the ratio between the observed basal area and a reference basal area above which  
241 avalanche release is impossible. Co-determinants are slope angle and the conifer-broadleaf ratio. The  
242 RPI quantifies the risk that a rock passes through a stand as the ratio of the maximal energy developed  
243 by the rock and the energy dissipated by the current forest stand. The required stand structural  
244 variables are the number of stems per hectare, the quadratic mean diameter of stems, the basal area  
245 per hectare and the basal area ratio of conifers to broadleaves. Additional variables include slope angle  
246 and the following, for which we assumed the mid-range values in parentheses suggested by  
247 Cordonnier et al. (2013): rock density (2,800 kg/m<sup>3</sup>), rock volume (1 m<sup>3</sup>), the initial fall height of the  
248 rock (20 m) and the length of the forested slope (250 m). The RPI is sensitive to these assumptions,  
249 which we accepted because the absolute values in the individual sample plots were less relevant for  
250 our study than the relative effect of management. The API and RPI values range between 0 and 1 (with  
251 1 = optimal protection). Both indices were only calculated for NFI plots that are within the protection  
252 perimeters for avalanches and rockfalls according to SilvaProtect (Losey and Wehrli, 2013) (Figure 1).

253

#### 254 **2.4.2 Aggregation of indicators**

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

263

### 264 2.4.3 Multi-criteria decision analysis

265 Management effects on ESB were analysed in ten-year time steps using MAVT (Ananda and Herath,  
 266 2009; Eisenführ et al., 2010; Kangas et al., 2015), an approach recently recommended for measuring  
 267 landscape ecosystem service multifunctionality (Manning et al., 2018). MAVT is based on utility theory  
 268 that assigns value functions to each indicator to represent the relationship between supply levels of  
 269 ESB and the benefit it provides to humans. This normalises the indicator values and results in utility  
 270 values of between 0 and 1 (with 1 = optimal indicator value) to allow comparison among ESB indicators.  
 271 In this study, we used linear transformations as value functions (Equation 1) (Manning et al., 2018; van  
 272 der Plas et al., 2016).

$$u(x_{i,j,k}) = \frac{x_{i,j,k} - \min_k}{\max_k - \min_k} \quad \text{Equation 1}$$

273 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  
 274 simulated indicator value,  $\max_k$  the maximum, and  $\min_k$  the minimum simulated indicator value over  
 275 all simulation intervals and scenarios in region (k).

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

$$\text{overall utility}_{i,j,k} = \sum_{a=1}^m \lambda_{a,k} \left( \sum_{b=1}^n \lambda_b u(x_{i,j,k}) \right) \quad \text{Equation 2}$$

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

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

280  
 281 where  $\lambda_b$  are the weights for indicators for a specific ESB, and  $\lambda_{a,k}$  are the weights for an ESB in region  
 282 (k). Indicator weights were defined using the simple multi-attribute rating technique (SMART) (Kangas  
 283 et al., 2015). Each indicator was given a rank according to its importance (high rank = important). The  
 284 corresponding indicator weight is calculated by the individual rank divided by the ESB-specific cross  
 285 sum of the assigned ranks. The definition of indicator-utility relationships (value functions) and  
 286 indicator weights were supported by a stakeholder panel, which consisted of three representatives of  
 287 forest policy-making (Federal Office for the Environment), two additional scientists (Swiss Federal  
 288 Institute WSL) and the authors. During a workshop, we discussed the general importance of each  
 289 indicator at the national scale and time horizon of this study.

290

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

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

294

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

306

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

310 \* There are no NFI sample plots within the SilvaProtect perimeter for rockfall and avalanche protection in the Plateau region.

311 Thus, a weight of zero for PGH was assigned for this region.

312

## 313 2.5 Trade-off analyses

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

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

$$RMSE_{j,k} = \sqrt{\frac{1}{n} \sum_{i=1}^n (ESB1_{i,j,k} - ESB2_{i,j,k})^2} \quad \text{Equation 3}$$

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

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

$$U_{ESB(i,j,k,l,GS_m)} = U_{ESB(i,j,k,l,GS_0)} \frac{a_w(GS_m(k))}{a_w(GS_0(k))} \quad \text{Equation 4}$$

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

$$nU_{ESB(i,j,k,l,GS_m)} = \frac{(U_{ESB(i,j,k,l,GS_m)} - U_{ESB(min,k)})}{(U_{ESB(max,k)} - U_{ESB(min,k)})} \quad \text{Equation 5}$$

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

338

## 339 **3 Results**

### 340 **3.1 Development of ecosystem services and biodiversity**

#### 341 **3.1.1 Timber production**

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

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

359

#### 360 **3.1.2 Carbon sequestration**

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

368 Overall, partial utilities for carbon sequestration decreased from 2006 to 2106 in the Plateau region by  
369 83% (*BAU*), 100% (*Constant*) and 74% (*Increment*), as well as 25% in the Pre-Alps under *BAU* (Figure 2).

370 However, this decrease resulted in an “overall” source of carbon only in the Plateau. All other scenarios  
371 and regions resulted in a carbon sink at the end of the simulation (Appendix S5.3).

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

376

### 377 **3.1.3 Protection against avalanche and rockfall**

378 The highest partial utilities for protection were projected for the Jura and the Pre-Alps under *Energy*  
379 with values of 0.33 and 0.44, respectively, at the end of the simulation (Figure 2). In contrast, under  
380 *BAU* the Alps (0.46), the Southern Alps (0.67) and the whole of Switzerland (0.49) had the highest  
381 values. The protection utilities for the protection forest perimeter throughout Switzerland increased  
382 by 4% by 2106 only under *BAU* while decreasing under all other scenarios (*Constant* -56%, *Increment* -  
383 67%, *Conifers* -47% and *Energy* -37%). Partial utilities for protection showed a humped development  
384 in almost all cases. These developments were controlled by the simulated increase in average DBH to  
385 which rockfall protection was positively and avalanche protection negatively related (cf. Appendix  
386 S5.4). A curvature in the development of both indices followed the unimodal development of the basal  
387 area, which was the result from MASSIMO-inherent routines for the simulation of protection forest  
388 management.

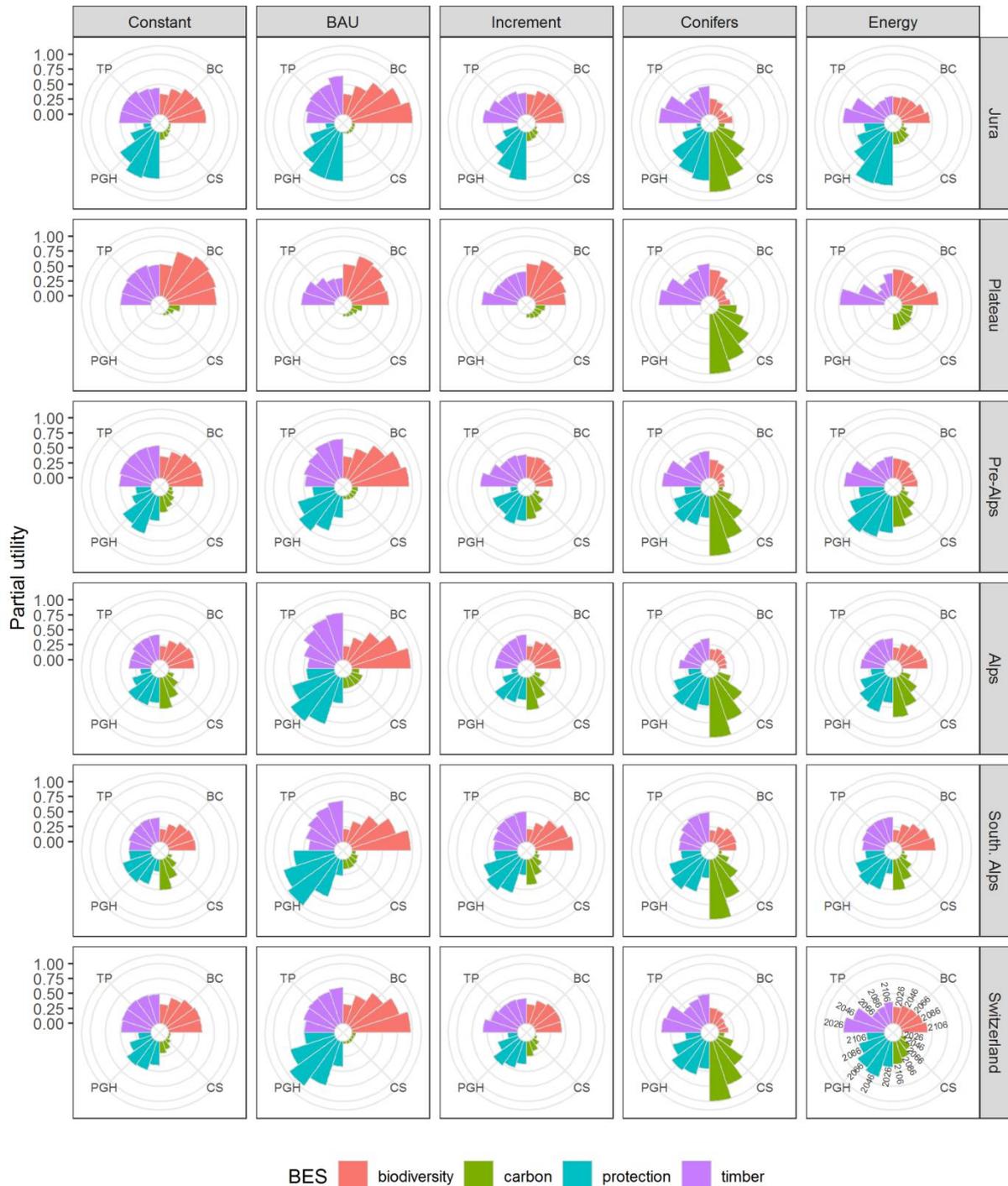
389

### 390 **3.1.4 Biodiversity conservation**

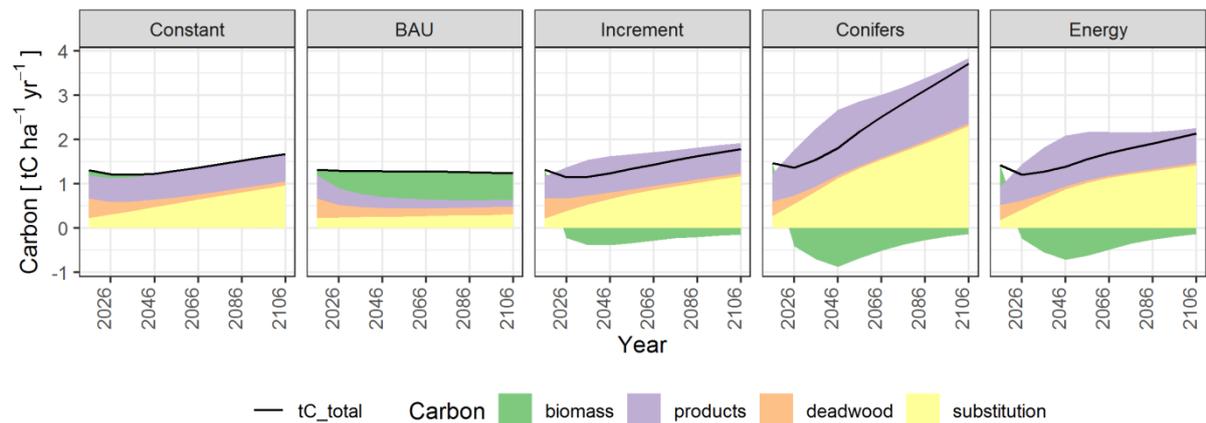
391 The highest partial utilities for biodiversity resulted under *BAU* (Figure 2) in all regions except for the  
392 Plateau. Values increased up to > 0.94 by the end of the simulation. The reason for this lies mainly in  
393 the low harvesting intensity (Appendix S5.1.2), which fostered deadwood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

398 Under the *Conifers* scenario, nearly constant (Jura > -7%) or decreasing (Plateau: -41%, Pre-Alps -63%,  
399 Alps -7%, Switzerland -20%) partial utilities were found for biodiversity. High harvesting activity under  
400 this scenario prevented the accumulation of deadwood and the retention of large living trees and  
401 reduced forest structural diversity. Further, species diversity decreased in response to the promotion  
402 of coniferous trees (Appendix S5.2.1). An exception was the Southern Alps region, where partial  
403 utilities increased slightly under *Conifers* because of the low harvest intensity in this region. Under the  
404 *Energy* scenario, in contrast, increasing partial utilities for biodiversity were found in all regions (>  
405 +82%), except for Pre-Alps where it decreased (-7%). The increase was caused by the established forest

406 reserves under *Energy*, which led to a positive effect on structural and species diversity and large living  
 407 trees (Appendix 5.2).  
 408



409  
 410 **Figure 2: Partial utilities of ecosystem services and biodiversity (ESB) simulated under the five management scenarios at**  
 411 **regional and national scales in Switzerland. Development over time is presented clockwise per ESB for the years 2026,**  
 412 **2046, 2066, 2086 and 2106 (legend shown for the region Switzerland and scenario Energy, bottom right).**  
 413



414

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

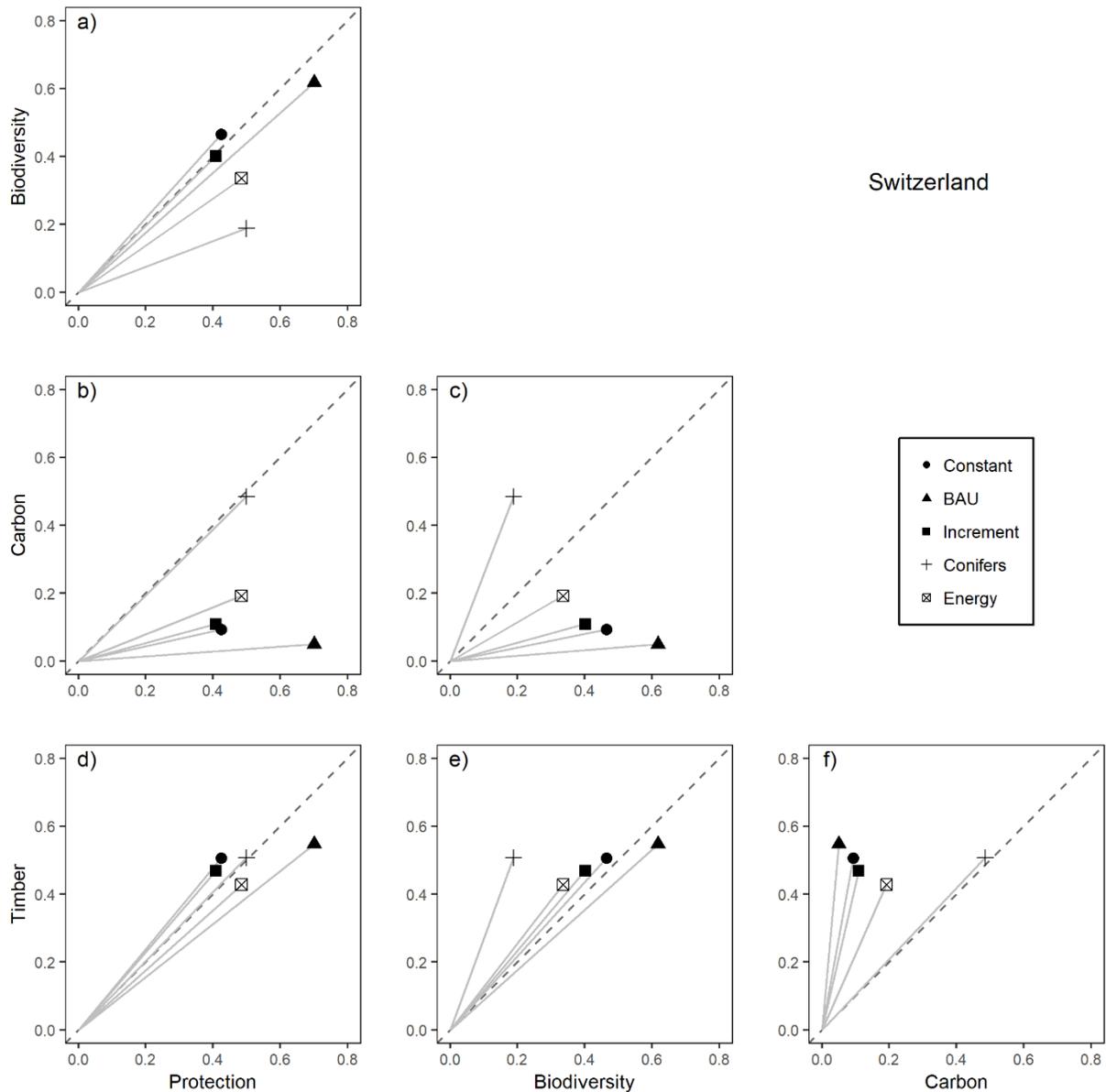
419

### 420 3.2 Trade-offs between individual ESB

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

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

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



435

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

439

### 440 3.3 Overall benefits and trade-offs

#### 441 3.3.1 Equal weights for ESB

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

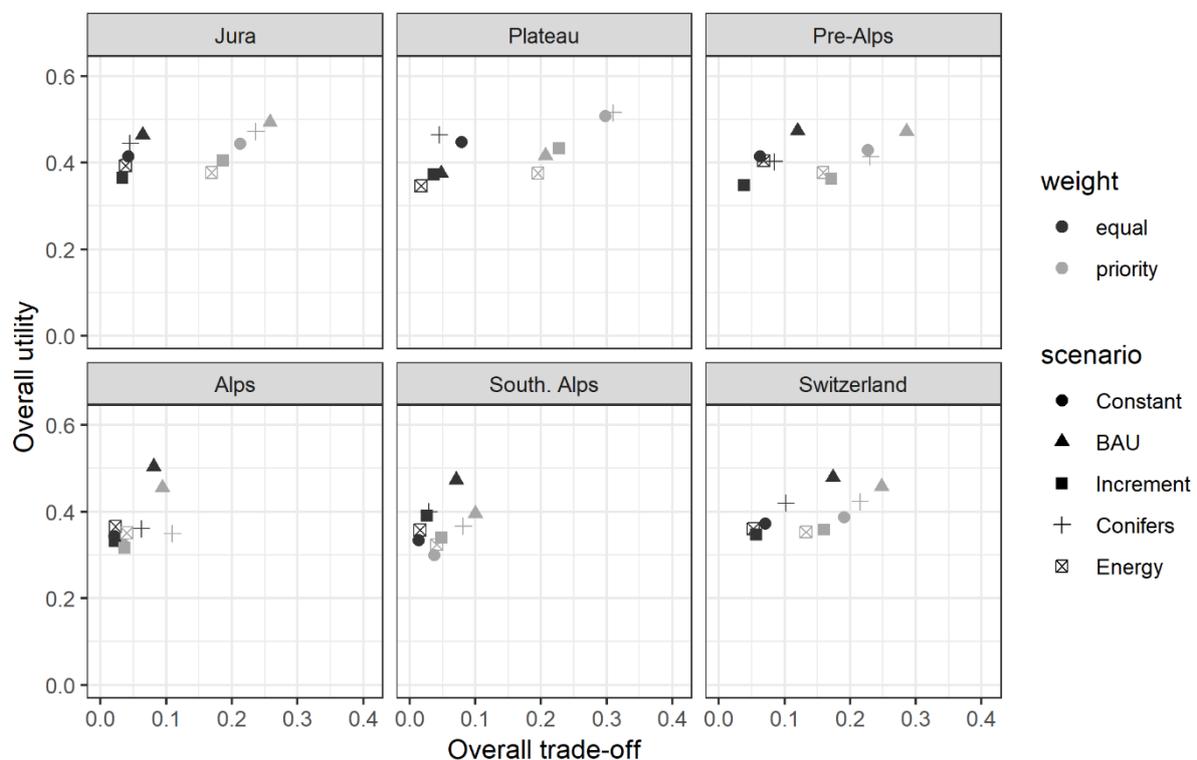
449 The scenarios with the highest benefits also exhibited the highest overall trade-offs. The *BAU* scenario  
 450 had an overall trade-off that ranges between 0.06 (Jura) and 0.17 (Switzerland). The most beneficial  
 451 scenarios for the Plateau region were *Constant* and *Conifers*, under which overall trade-off values of  
 452 0.08 and 0.05 were reached, respectively.

### 453 3.3.2 Management priorities for ESB

454 The weighting variant according to the primary management objective per region increased benefits,  
 455 reaching the highest values in the Jura (+7% for *BAU*) and Plateau (+13% for *Constant* and *Conifers*)  
 456 regions. In the Pre-Alps region, the value under *BAU* remained constant, while decreasing in the Alps  
 457 (-8%), Southern Alps (-15%) and Switzerland (-4%).

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

464



465

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

468

## 469 **4 Discussion and conclusion**

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

### 478 **4.1 Ecosystem services and biodiversity**

#### 479 **4.1.1 Timber production**

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

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

503 al. (2007) applied local value functions with a bell-shaped curve for growing stocks, which led to  
504 decreasing utility values for extensive or unmanaged forests with high growing stocks.

505

#### 506 **4.1.2 Carbon sequestration**

507 Carbon sequestration and its sensitivity to forest management is of great interest in the context of  
508 climate-change mitigation (Bellassen and Luysaert, 2014; Nabuurs et al., 2018). Forests can be  
509 structured through systematic interventions in such a way that their rate of CO<sub>2</sub> absorption increases  
510 (e.g., Thürig and Kaufmann (2010); Zanchi et al. (2014)). Additionally, it is important to account for  
511 carbon storage in wood products as well as the aspect of substitution to evaluate the contribution of  
512 forest management to the mitigation of greenhouse gases comprehensively (Nabuurs et al., 2017;  
513 Werner et al., 2010). For this study, we adapted the methodology for carbon assessment of Blattert et  
514 al. (2018) to account for such ex-situ carbon storages (cf. section 2.4.1).

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

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

530

#### 531 **4.1.3 Protection against gravitational hazards**

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

537 S5.2.4), which in turn leads to forest conditions that are vulnerable to several disturbances (Bebi et al.,  
538 2017; Temperli et al., in review). In contrast, guaranteeing optimal protection in the long-term requires  
539 sufficient regeneration and younger trees to sustain a stable stand structure (Brang et al., 2008;  
540 Frehner et al., 2007).

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

553

#### 554 **4.1.4 Biodiversity conservation**

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

560 Our results are in accordance with other MCDA studies that investigated biodiversity aspects under  
561 different management scenarios (Carpentier et al., 2016; Diaz-Balteiro et al., 2017; Mina et al., 2017).  
562 Many of these found scenarios with extensive or no management to be most beneficial for biodiversity.  
563 However, such studies only assessed indicators that measure structural attributes found in late  
564 successional stages (e.g., deadwood from mortality and habitat trees). We additionally assessed tree  
565 size and species diversity as did Langner et al. (2017). The deadwood pools in our simulations also  
566 included harvesting residues, which can also provide valuable biotopes for deadwood-dependent  
567 species (Lachat et al., 2014; Ranius et al., 2018). Our results predicted deadwood pools of greater than  
568 50 m<sup>3</sup> per hectare for all scenarios Swiss-wide. However, these pools consisted mainly of fine wood  
569 litter under the *Conifer* and *Energy* scenarios, particularly in the Jura, Plateau and Pre-Alps (see  
570 Appendix S5.2.3). While such values comply with recommended target thresholds for biodiversity  
571 conservations (Müller and Bütler, 2010), they may also result from decay rates for fine woody litter

572 that have little empirical basis, implying that there is a potential underestimation of litter decay. Hence,  
573 these deadwood pools need to be interpreted cautiously.

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

586

## 587 **4.2 Trade-offs arising from scenarios**

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

595 The scenarios with the highest ESB benefit per region showed simultaneously the highest overall trade-  
596 offs (Figure 5). Furthermore, weighting ESB according to regional management priorities increased the  
597 trade-off situation while also increasing the overall benefits of harvesting scenarios, apart from the  
598 mountainous region Alps and Southern Alps, where benefits decreased. A similar decreasing effect in  
599 mountainous areas was also reported by Langner et al. (2017), who investigated trade-offs in several  
600 European mountain case studies. Strong trade-offs were found between the carbon sequestration  
601 objective and all other objectives. In contrast, trade-offs were weak between biodiversity aims and the  
602 services timber production and protection (Figure 4). This result differs from most other studies that  
603 have investigated these objectives. For example, Mina et al. (2017) found synergy effects between  
604 carbon and biodiversity and protection under scenarios with extensive or no management. Synergies  
605 were also found between carbon sequestration and biodiversity (habitat) by Gutsch et al. (2018).  
606 However, both studies only accounted for in-situ carbon sequestrations (cf. Section 4.1.2). Further,

607 most other studies have also identified trade-offs between timber production and biodiversity (e.g.,  
608 Gutsch et al. (2018); Lafond et al. (2017); Mina et al. (2017)). However, these studies assessed timber  
609 production mainly by harvested timber volumes, whereas we also included economic aspects (cf.  
610 Section 3.1.1), which have a decisive influence on the economically sustainable amount of biomass  
611 that can be harvested. In contrast, this study is in line with others that also found a synergistic  
612 relationship or lack of trade-off between biodiversity and protection (Lafond et al., 2017; Mina et al.,  
613 2017).

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

619

### 620 **4.3 Analysis framework**

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

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

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

642 The current set of management scenarios may be extended by adaptation scenarios that increase the  
643 resilience of forests against the uncertainty of cumulative global changes. Messier et al. (2019) advise  
644 to use the most efficient forest management and silvicultural practices and to manage forests as  
645 complex adaptive networks to increase the resistance and resilience capacity of forests. Close to nature  
646 management methods like single-tree selection, group selection and shelterwood, which are widely  
647 applied in Switzerland, are a promising approach to increase the adaptive capacity of forests, since it  
648 promotes structural diversity and tree resistance to stressors (Brang et al., 2014). Those methods can  
649 further be improved by increasing tree species richness, also by non-local provenances (Frank et al.,  
650 2017) or even non-native species (Brang et al., 2016). Non-native tree species currently recommended  
651 for Switzerland are Douglas fir (*Pseudotsuga menziesii*), large coastal fir (*Abies grandis*) and oriental  
652 beech (*Fagus orientalis*), if they are planted in mixture with native tree species and outside of forest  
653 communities of high conservation value (Brang et al., 2016). Especially, non-native coniferous tree-  
654 species can reduce the risks of climate change for ecosystem services like timber production and  
655 carbon sequestration and could be a valuable alternative to spruce within the *Conifers* scenario in the  
656 future.

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

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

693

#### 694 **4.4 Implications for forest management**

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

701 Our study indicates that, apart from the Plateau, current management practice in Switzerland (*BAU*)  
702 provides the highest ESB benefits. However, under *BAU*, possible timber potentials are not mobilised,  
703 which are highly recommended by the Swiss Forest Policy to foster the forestry and timber sector and  
704 to mitigate the effects of climate change (BAFU, 2013; BAFU et al., 2014). In the Plateau region, ESB  
705 benefits were highest under the constant growing stock scenario by additionally guaranteeing long-  
706 term and sustainable timber usage. Nevertheless, both management scenarios (*BAU*, *Constant*)  
707 showed a strong trade-off between biodiversity conservation and carbon sequestration. The latter  
708 service is achieved best under a scenario promoting coniferous timber utilisation (*Conifers*), which, in  
709 turn, provides wood for long-living construction materials and substitutes non-timber and energy  
710 intensive products. Considering regional management priorities strongly increased the overall trade-

711 off situation, particularly in lowland regions. We thus conclude that no single management strategy is  
712 appropriate to maximize the provision of multiple ESB simultaneously. A targeted combination of  
713 forest stand management strategies with different dominant management objectives can lead to a  
714 higher degree of multifunctionality at the landscape level than one forest management practice  
715 (Lagergren and Jönsson, 2017). Such a segregation of the forest landscape offers a compromise by  
716 combining the positive aspects of several management scenarios to best achieve multiple forest policy  
717 objectives. This has been recommended by several studies (e.g., Blattert et al. (2018); Carpentier et al.  
718 (2016); Côté et al. (2010); Messier et al. (2009)). Nevertheless, management in order to support ESB  
719 should be evaluated carefully at the local (stand) scale, as the most advantageous scenario clearly  
720 depends on the specific needs of ESB (Mina et al., 2017). For example, protection against avalanches  
721 and rockfall cannot be balanced against other objectives in most cases, but is simply necessary to save  
722 lives.

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

729

## 730 **5 Acknowledgements**

731 We thank Steffen Herrmann for providing the deadwood decomposition factors and the two reviewers  
732 for helpful comments improving the quality of the paper. The Swiss NFI program (by the Federal Office  
733 of Environment FOEN and the Federal Institute for Forest, Snow and Landscape research WSL) funded  
734 this research.

735 **6 References**

- 736 Ananda, J., Herath, G., 2009. A critical review of multi-criteria decision making methods with special  
737 reference to forest management and planning. *Ecological Economics* 68, 2535-2548.
- 738 BAFU, 2012. Strategie Biodiversität Schweiz. Bundesamt für Umwelt, Bern, p. 89.
- 739 BAFU, 2013. Waldpolitik 2020 - Visionen, Ziele und Massnahmen für eine nachhaltige  
740 Bewirtschaftung des Schweizer Waldes. Bundesamt für Umwelt, Bern, p. 66.
- 741 BAFU, BFE, SECO, 2014. Ressourcenpolitik Holz. Strategie, Ziele und Aktionsplan Holz, Bern, p. 36.
- 742 Bebi, P., Seidl, R., Motta, R., Fuhr, M., Firm, D., Krumm, F., Conedera, M., Ginzler, C., Wohlgemuth, T.,  
743 Kulakowski, D., 2017. Changes of forest cover and disturbance regimes in the mountain forests of the  
744 Alps. *Forest Ecology and Management* 388, 43-56.
- 745 Bellassen, V., Luyssaert, S., 2014. Carbon sequestration: managing forests in uncertain times. *Nature*  
746 506, 153-155.
- 747 Berger, F., Dorren, L., 2007. Principles of the tool Rockfor.net for quantifying the rockfall hazard  
748 below a protection forest. *Schweiz. Z. Forstwes.* 158, 157-165.
- 749 Bernasconi, A., Gubsch, M., Hasspacher, B., Iseli, R., Stillhard, J., 2014. Präzisierung Basis-Indikatoren  
750 Nachhaltigkeitskontrolle Wald. Bundesamt für Umwelt BAFU, Bern, p. 57.
- 751 Blattert, C., Lemm, R., Thees, O., Hansen, J., Lexer, M.J., Hanewinkel, M., 2018. Segregated versus  
752 integrated biodiversity conservation: Value-based ecosystem service assessment under varying forest  
753 management strategies in a Swiss case study. *Ecological Indicators* 95, 751-764.
- 754 Blattert, C., Lemm, R., Thees, O., Lexer, M.J., Hanewinkel, M., 2017. Management of ecosystem  
755 services in mountain forests: Review of indicators and value functions for model based multi-criteria  
756 decision analysis. *Ecological Indicators* 79, 391-409.
- 757 Bradford, J.B., D'Amato, A.W., 2012. Recognizing trade-offs in multi-objective land management.  
758 *Frontiers in Ecology and the Environment* 10, 210-216.
- 759 Brang, P., Pluess, A., Bürgi, A., Born, J., 2016. Potenzial von Gastbaumarten bei der Anpassung an den  
760 Klimawandel, pp. 385-405.
- 761 Brang, P., Schönenberger, W., Ott, E., Gardner, B., 2008. Forests as Protection from Natural Hazards,  
762 *The Forests Handbook*. Blackwell Science Ltd, pp. 53-81.
- 763 Brang, P., Spathelf, P., Larsen, J., Bauhus, J., Boncina, A., Chauvin, C., Drössler, L., García-Güemes, C.,  
764 Heiri, C., Kerr, G., Lexer, M., Mason, B., Mohren, G.M.J., Mühlethaler, U., Nocentini, S., Svoboda, M.,  
765 2014. Suitability of close-to-nature silviculture for adapting temperate European forests to climate  
766 change. *Forestry* 87, 492-503.
- 767 Briceño-Elizondo, E., Jäger, D., Lexer, M.J., Garcia-Gonzalo, J., Peltola, H., Kellomäki, S., 2008. Multi-  
768 criteria evaluation of multi-purpose stand treatment programmes for Finnish boreal forests under  
769 changing climate. *Ecological Indicators* 8, 26-45.
- 770 Brändli, U.B., 2010. Schweizerisches Landesforstinventar. Ergebnisse der dritten Erhebung 2004-  
771 2006. Eidg. Forschungsanstalt WSL, Bundesamt für Umwelt BAFU, Birmensdorf, Bern, p. 312.
- 772 Brändli, U.B., Hägeli, M., 2019 NFI at a Glance, in: Fischer, C., Traub, B. (Eds.), *Swiss National Forest*  
773 *Inventory — Methods and Models of the Fourth Assessment* (in print). Springer.
- 774 Bugmann, H., Cordonnier, T., Truhetz, H., Lexer, M.J., 2017. Impacts of business-as-usual  
775 management on ecosystem services in European mountain ranges under climate change. *Regional*  
776 *Environmental Change* 17, 3-16.

- 777 Carpentier, S., Filotas, E., Handa, I.T., Messier, C., 2016. Trade-offs between timber production,  
778 carbon stocking and habitat quality when managing woodlots for multiple ecosystem services.  
779 *Environmental Conservation* 44, 14-23.
- 780 Cordonnier, T., Berger, F., Elkin, C., Låmas, T., Martinez, M., 2013. ARANGE Deliverable D2.2 - Models  
781 and linker functions (indicators) for ecosystem services.
- 782 Côté, P., Tittler, R., Messier, C., Kneeshaw, D.D., Fall, A., Fortin, M.J., 2010. Comparing different forest  
783 zoning options for landscape-scale management of the boreal forest: Possible benefits of the TRIAD.  
784 *Forest Ecology and Management* 259, 418-427.
- 785 Diaz-Balteiro, L., Alonso, R., Martínez-Jaúregui, M., Pardos, M., 2017. Selecting the best forest  
786 management alternative by aggregating ecosystem services indicators over time: A case study in  
787 central Spain. *Ecological Indicators* 72, 322-329.
- 788 Dorren, L., Berger, F., Frehner, M., Huber, M., Kühne, K., Métral, R., Sandri, A., Schwitter, R.,  
789 Thormann, J.-J., Wasser, B., 2015. Das neue NaiS-Andforderungsprofil Steinschlag. *Schweiz. Z.*  
790 *Forstwes.* 166, 16-23.
- 791 EASAC, 2017. Multi-functionality and sustainability in the European Union's forests. EASAC policy  
792 report 32. European Academies' Science Advisory Council, p. 43.
- 793 Eisenführ, F., Weber, M., Langer, T., 2010. Rational decision making. Berlin : Springer.
- 794 Elkin, C., Gutiérrez, A.G., Leuzinger, S., Manusch, C., Temperli, C., Rasche, L., Bugmann, H., 2013. A  
795 2 °C warmer world is not safe for ecosystem services in the European Alps. *Global Change Biology* 19,  
796 1827-1840.
- 797 Etzold, S., Ziemińska, K., Rohner, B., Bottero, A., Bose, A.K., Ruehr, N.K., Zingg, A., Rigling, A., 2019.  
798 One Century of Forest Monitoring Data in Switzerland Reveals Species- and Site-Specific Trends of  
799 Climate-Induced Tree Mortality. *Frontiers in Plant Science* 10.
- 800 EU, 2018. Regulation (EU) 2018/841 of the European Parliament and of the Council of 30 May 2018 on  
801 the inclusion of greenhouse gas emissions and removals from land use, land use change and forestry  
802 in the 2030 climate and energy framework, and amending Regulation (EU) No 525/2013 and Decision  
803 No 529/2013/EU. *Official Journal of the European Union*, 1-25.
- 804 European Commission, 2018. A Clean Planet for all. A European strategic long-term vision for a  
805 prosperous, modern, competitive and climate neutral economy. COM(2018) 773 final Brussel, p. 25.
- 806 Felipe-Lucia, M.R., Soliveres, S., Penone, C., Manning, P., van der Plas, F., Boch, S., Prati, D., Ammer,  
807 C., Schall, P., Gossner, M.M., Bauhus, J., Buscot, F., Blaser, S., Blüthgen, N., de Frutos, A., Ehbrecht,  
808 M., Frank, K., Goldmann, K., Hänsel, F., Jung, K., Kahl, T., Nauss, T., Oelmann, Y., Pena, R., Polle, A.,  
809 Renner, S., Schloter, M., Schöning, I., Schrupf, M., Schulze, E.-D., Solly, E., Sorkau, E., Stempfhuber,  
810 B., Tschapka, M., Weisser, W.W., Wubet, T., Fischer, M., Allan, E., 2018. Multiple forest attributes  
811 underpin the supply of multiple ecosystem services. *Nature Communications* 9, 4839.
- 812 Ferranti, F., 2014. Energy wood: A challenge for European forests. Potentials, environmental  
813 implications, policy integration and related conflicts. *Europea Forest Institute EFI*, p. 158.
- 814 Frank, A., Howe, G.T., Sperisen, C., Brang, P., Clair, J.B.S., Schmatz, D.R., Heiri, C., 2017. Risk of genetic  
815 maladaptation due to climate change in three major European tree species. *Global Change Biology*  
816 23, 5358-5371.
- 817 Frehner, M., Wasser, B., Schwitter, R., 2007. Sustainability and success monitoring in protection  
818 forests. Guidelines for managing forests with protective functions. Federal Office for the  
819 Environment FOEN, Bern.
- 820 Frutig, F., Thees, O., Lemm, R., Kostadinov, F., 2009. Holzernteproduktivitätsmodelle HeProMo -  
821 Kenzeption, Realisierung, Nutzung und Weiterentwicklung, in: Thees, O., Lemm, R. (Eds.),

- 822 Management zukunftsfähige Waldnutzung. Grundlagen, Methoden und Instrumente. vdf  
823 Hochschulverlag, Birmensdorf, Eidg. Forschungsanstalt WSL, pp. 441-466.
- 824 Fürstenau, C., Badeck, F.W., Lasch, P., Lexer, M.J., Lindner, M., Mohr, P., Suckow, F., 2007. Multiple-  
825 use forest management in consideration of climate change and the interests of stakeholder groups.  
826 *European Journal of Forest Research* 126, 225-239.
- 827 Gutsch, M., Lasch-Born, P., Kollas, C., Suckow, F., Reyer, C.P.O., 2018. Balancing trade-offs between  
828 ecosystem services in Germany's forests under climate change. *Environmental Research Letters* 13,  
829 045012.
- 830 Hanewinkel, M., Cullmann, D.A., Schelhaas, M.-J., Nabuurs, G.-J., Zimmermann, N.E., 2013. Climate  
831 change may cause severe loss in the economic value of European forest land. *Nature Clim. Change* 3,  
832 203-207.
- 833 Hetemäki, L., Hanewinkel, M., Muys, B., Ollikainen, M., Palahí, M., Trasobares, A., 2017. Leading the  
834 way to a European circular bioeconomy strategy. *From Science to Policy* 5. European Forest Institute,  
835 p. 50.
- 836 Hilmers, T., Friess, N., Bässler, C., Heurich, M., Brandl, R., Pretzsch, H., Seidl, R., Müller, J., 2018.  
837 Biodiversity along temperate forest succession. *Journal of Applied Ecology* 0.
- 838 Hoogstra-Klein, M.A., Hengeveld, G.M., de Jong, R., 2017. Analysing scenario approaches for forest  
839 management — One decade of experiences in Europe. *Forest Policy and Economics* 85, 222-234.
- 840 Huber, M., Brang, P., Sandri, A., 2015. Protection against natural hazards, in: Rigling, A., Schaffer, H.P.  
841 (Eds.), *Forest Report 2015. Condition and Use of Swiss Forests*. Federal Office for the Environment  
842 (FOEN), Bern, Swiss Federal Institute for Forest Snow and Landscape Research (WSL), Birmensdorf,  
843 pp. 94-97.
- 844 Irauschek, F., Rammer, W., Lexer, M.J., 2017. Evaluating multifunctionality and adaptive capacity of  
845 mountain forest management alternatives under climate change in the Eastern Alps. *European*  
846 *Journal of Forest Research*, 1-19.
- 847 Jandl, R., Ledermann, T., Kindermann, G., Freudenschuss, A., Gschwantner, T., Weiss, P., 2018.  
848 *Strategies for Climate-Smart Forest Management in Austria*. *Forests* 9, 592.
- 849 Jost, L., 2007. Partitioning diversity into independent alpha and beta components. *Ecology* 88, 2427-  
850 2439.
- 851 Kangas, A., Kurttila, M., Hujala, T., Eyvindson, K., Kangas, J., 2015. *Decision Support for Forest*  
852 *Management - Second Edition*. Springer.
- 853 Klemperer, W.D., 1996. *Forest resource economics and finance*. McGraw-Hill, New York.
- 854 Kraus, D., Krumm, F., 2013. Integrative approaches as an opportunity for the conservation of forest  
855 biodiversity. European Forest Institute EFI.
- 856 Lachat, T., Brang, P., Bolliger, M., Bollmann, K., Herrmann, S., Schneider, O., Wermelinger, B., 2014.  
857 *Totholz im Wald. Entstehung, Bedeutung und Förderung*, *Merkbl. Prax. Eidg. Forschungsanstalt WSL*,  
858 Birmensdorf, p. 12.
- 859 Lafond, V., Cordonnier, T., Mao, Z., Courbaud, B., 2017. Trade-offs and synergies between ecosystem  
860 services in uneven-aged mountain forests: evidences using Pareto fronts. *European Journal of Forest*  
861 *Research* 136, 997-1012.
- 862 Lagergren, F., Jönsson, A.M., 2017. Ecosystem model analysis of multi-use forestry in a changing  
863 climate. *Ecosystem Services* 26, 209-224.
- 864 Langner, A., Irauschek, F., Perez, S., Pardos, M., Zlatanov, T., Öhman, K., Nordström, E.-M., Lexer,  
865 M.J., 2017. Value-based ecosystem service trade-offs in multi-objective management in European  
866 mountain forests. *Ecosystem Services* 26, 245-257.

- 867 Leskinen, P., Cardellini, G., González-García, S., Hurmekoski, E., Sathre, R., Seppälä, J., Smyth, C.,  
868 Verkerk, P.J., 2018. Substitution effects of wood-based products in climate change mitigation. From  
869 Science to Policy 7. European Forest Institute, p. 27.
- 870 Lexer, M.J., Bugmann, H., 2017. Mountain forest management in a changing world. *European Journal*  
871 *of Forest Research* 136, 981-982.
- 872 Losey, S., Wehrli, A., 2013. Schutzwald in der Schweiz. Vom Projekt SilvaProtect-CH zum  
873 harmonisierten Schutzwald. Bundesamt für Umwelt, Bern, p. 29.
- 874 Manning, P., van der Plas, F., Soliveres, S., Allan, E., Maestre, F.T., Mace, G., Whittingham, M.J.,  
875 Fischer, M., 2018. Redefining ecosystem multifunctionality. *Nature Ecology & Evolution* 2, 427-436.
- 876 Marini, L., Økland, B., Jönsson, A.M., Bentz, B., Carroll, A., Forster, B., Grégoire, J.-C., Hurling, R.,  
877 Nageleisen, L.M., Netherer, S., Ravn, H.P., Weed, A., Schroeder, M., 2017. Climate drivers of bark  
878 beetle outbreak dynamics in Norway spruce forests. *Ecography* 40, 1426-1435.
- 879 MEA, 2005. Millenium Ecosystem Assessment - Ecosystem and Human Well-being: Snthesis. Island  
880 Press, Washington, DC.
- 881 Messier, C., Bauhus, J., Doyon, F., Maure, F., Sousa-Silva, R., Nolet, P., Mina, M., Aquilué, N., Fortin,  
882 M.-J., Puettmann, K., 2019. The functional complex network approach to foster forest resilience to  
883 global changes. *Forest Ecosystems* 6, 21.
- 884 Messier, C., Tittler, R., Kneeshaw, D.D., Gélinas, N., Paquette, A., Berninger, K., Rheault, H., Meek, P.,  
885 Beaulieu, N., 2009. TRIAD zoning in Quebec: Experiences and results after 5 years. *Forestry Chronicle*  
886 85, 885-896.
- 887 Mina, M., Bugmann, H., Cordonnier, T., Irauschek, F., Klopčič, M., Pardos, M., Cailleret, M., 2017.  
888 Future ecosystem services from European mountain forests under climate change. *Journal of Applied*  
889 *Ecology* 54, 389-401.
- 890 Moning, C., Müller, J., 2009. Critical forest age thresholds for the diversity of lichens, molluscs and  
891 birds in beech (*Fagus sylvatica* L.) dominated forests. *Ecological Indicators* 9, 922-932.
- 892 Moos, C., Bebi, P., Schwarz, M., Stoffel, M., Sudmeier-Rieux, K., Dorren, L., 2018. Ecosystem-based  
893 disaster risk reduction in mountains. *Earth-Science Reviews* 177, 497-513.
- 894 Müller, J., Bütler, R., 2010. A review of habitat thresholds for dead wood: A baseline for management  
895 recommendations in European forests. *European Journal of Forest Research* 129, 981-992.
- 896 Myllyviita, T., Hujala, T., Kangas, A., Leskinen, P., 2011. Decision Support in Assessing the Sustainable  
897 Use of Forests and Other Natural Resources - A Comparative Review. *The Open Forest Science*  
898 *Journal* 4, 24-41.
- 899 Nabuurs, G.-J., Arets, E.J.M.M., Schelhaas, M.-J., 2018. Understanding the implications of the EU-  
900 LULUCF regulation for the wood supply from EU forests to the EU. *Carbon Balance and Management*  
901 13, 18.
- 902 Nabuurs, G.-J., Delacote, P., David, E., Hanewinkel, M., Hetemäki, L., Lindner, M., 2017. By 2050 the  
903 Mitigation Effects of EU Forests Could Nearly Double through Climate Smart Forestry.
- 904 Olander, L., Polasky, S., Kagan, J.S., Johnston, R.J., Wainger, L., Saah, D., Maguire, L., Boyd, J.,  
905 Yoskowitz, D., 2017. So you want your research to be relevant? Building the bridge between  
906 ecosystem services research and practice. *Ecosystem Services* 26, 170-182.
- 907 Pardos, M., Pérez, S., Calama, R., Alonso, R., Lexer, M.J., 2016. Ecosystem service provision,  
908 management systems and climate change in Valsain forest, central Spain. *Regional Environmental*  
909 *Change*, 1-16.

- 910 Perez-Garcia, J., Lippke, B., Comnick, J., Manriquez, C., 2005. An assessment of carbon pools, storage,  
911 and wood products market substitution using life-cycle analysis results. *Wood and Fiber Science* 37,  
912 140-148.
- 913 Pukkala, T., 2014. Does biofuel harvesting and continuous cover management increase carbon  
914 sequestration? *Forest Policy and Economics* 43, 41-50.
- 915 Ranius, T., Hämäläinen, A., Egnell, G., Olsson, B., Eklöf, K., Stendahl, J., Rudolphi, J., Sténs, A., Felton,  
916 A., 2018. The effects of logging residue extraction for energy on ecosystem services and biodiversity:  
917 A synthesis. *Journal of Environmental Management* 209, 409-425.
- 918 Reyer, C., Lasch-Born, P., Suckow, F., Gutsch, M., Murawski, A., Pilz, T., 2014. Projections of regional  
919 changes in forest net primary productivity for different tree species in Europe driven by climate  
920 change and carbon dioxide. *Annals of Forest Science* 71, 211-225.
- 921 Rohner, B., Waldner, P., Lischke, H., Ferretti, M., Thürig, E., 2018. Predicting individual-tree growth of  
922 central European tree species as a function of site, stand, management, nutrient, and climate effects.  
923 *European Journal of Forest Research* 137, 29-44.
- 924 Rosenvald, R., Löhmus, A., Kraut, A., Remm, L., 2011. Bird communities in hemiboreal old-growth  
925 forests: The roles of food supply, stand structure, and site type. *Forest Ecology and Management*  
926 262, 1541-1550.
- 927 Schall, P., Gossner, M.M., Heinrichs, S., Fischer, M., Boch, S., Prati, D., Jung, K., Baumgartner, V.,  
928 Blaser, S., Böhm, S., Buscot, F., Daniel, R., Goldmann, K., Kaiser, K., Kahl, T., Lange, M., Müller, J.,  
929 Overmann, J., Renner, S.C., Schulze, E.-D., Sikorski, J., Tschapka, M., Türke, M., Weisser, W.W.,  
930 Wemheuer, B., Wubet, T., Ammer, C., 2017. The impact of even-aged and uneven-aged forest  
931 management on regional biodiversity of multiple taxa in European beech forests. *Journal of Applied*  
932 *Ecology* 55, 267-278.
- 933 Schmid, S., Thürig, E., Kaufmann, E., Lischke, H., Bugmann, H., 2006. Effect of forest management on  
934 future carbon pools and fluxes: A model comparison. *Forest Ecology and Management* 237, 65-82.
- 935 Schwenk, W.S., Donovan, T.M., Keeton, W.S., Nunery, J.S., 2012. Carbon storage, timber production,  
936 and biodiversity: Comparing ecosystem services with multi-criteria decision analysis. *Ecological*  
937 *Applications* 22, 1612-1627.
- 938 Seidl, R., Honkaniemi, J., Aakala, T., Aleinikov, A., Angelstam, P., Bouchard, M., Boulanger, Y., Burton,  
939 P.J., De Grandpré, L., Gauthier, S., Hansen, W.D., Jepsen, J.U., Jöngiste, K., Kneeshaw, D.D.,  
940 Kuuluvainen, T., Lisitsyna, O., Makoto, K., Mori, A.S., Pureswaran, D.S., Shorohova, E., Shubnitsina, E.,  
941 Taylor, A.R., Vladimirova, N., Vodde, F., Senf, C., 2020. Globally consistent climate sensitivity of  
942 natural disturbances across boreal and temperate forest ecosystems. *Ecography* 43, 1-12.
- 943 Seidl, R., Rammer, W., Jäger, D., Currie, W.S., Lexer, M.J., 2007. Assessing trade-offs between carbon  
944 sequestration and timber production within a framework of multi-purpose forestry in Austria. *Forest*  
945 *Ecology and Management* 248, 64-79.
- 946 Seidl, R., Thom, D., Kautz, M., Martin-Benito, D., Peltoniemi, M., Vacchiano, G., Wild, J., Ascoli, D.,  
947 Petr, M., Honkaniemi, J., Lexer, M.J., Trotsiuk, V., Mairota, P., Svoboda, M., Fabrika, M., Nagel, T.A.,  
948 Reyer, C.P.O., 2017. Forest disturbances under climate change. *nature Clim. Change* 7, 395-402.
- 949 Shannon, C.E., Weaver, W., 1949. *The mathematical theory of communication*. Urbana, Ill. :  
950 University of Illinois Press.
- 951 Stadelmann, G., Bugmann, H., Wermelinger, B., Bigler, C., 2014. Spatial interactions between storm  
952 damage and subsequent infestations by the European spruce bark beetle. *Forest Ecology and*  
953 *Management* 318, 167-174.

- 954 Stadelmann, G., Herold, A., Didion, M., Vidondo, B., Gomez, A., Thürig, E., 2016. Holzerntepotenzial  
955 im Schweizer Wald: Simulation von Bewirtschaftungsszenarien. Schweizerische Zeitschrift für  
956 Forstwesen 167, 152-161.
- 957 Stadelmann, G., Temperli, C., Rohner, B., Didion, M., Herold, A., Rösler, E., Thürig, E., 2019.  
958 Presenting MASSIMO: A Management Scenario Simulation Model to Project Growth, Harvests and  
959 Carbon Dynamics of Swiss Forests. *Forests* 10, 1-18.
- 960 Staudhammer, C.L., LeMay, V.M., 2001. Introduction and evaluation of possible indices of stand  
961 structural diversity. *Canadian Journal of Forest Research* 31, 1105-1115.
- 962 Taverna, R., Gautschi, M., Hofer, P., 2016. Das nachhaltig verfügbare Holznutzungspotenzial im  
963 Schweizer Wald. Schweizerische Zeitschrift für Forstwesen 167, 162-171.
- 964 Taverna, R., Hofer, P., Werner, F., Kaufmann, E., Thürig, E., 2007. CO<sub>2</sub>-Effekte der Schweizer Wald-  
965 und Holzwirtschaft: Szenarien zukünftiger Beiträge zum Klimaschutz. Bundesamt für Umwelt BAFU,  
966 Bern.
- 967 Temperli, C., Blattert, C., Stadelmann, G., Brändli, U.B., Thürig, E., in review. Does the prevention  
968 trade-off with ecosystem service provision in Swiss forests? *Journal of Environmental Management*.
- 969 Temperli, C., Bugmann, H., Elkin, C., 2013. Cross-scale interactions among bark beetles, climate  
970 change, and wind disturbances: a landscape modeling approach. *Ecological Monographs* 83, 383-402.
- 971 Temperli, C., Stadelmann, G., Thürig, E., Brang, P., 2017a. Silvicultural strategies for increased timber  
972 harvesting in a Central European mountain landscape. *European Journal of Forest Research* 136, 493-  
973 509.
- 974 Temperli, C., Stadelmann, G., Thürig, E., Brang, P., 2017b. Timber mobilization and habitat tree  
975 retention in low-elevation mixed forests in Switzerland: an inventory-based scenario analysis of  
976 opportunities and constraints. *European Journal of Forest Research* 136, 711-725.
- 977 Thees, O., Burg, V., Erni, M., Bowman, G., Lemm, R., 2017. Biomassepotenziale der Schweiz für die  
978 energetische Nutzung, Schlussbericht SCCER Biosweet, WSL Bericht. Eidg. Forschungsanstalt WSL,  
979 Birmensdorf, p. 299.
- 980 Thees, O., Schmid, S., 2015. Social Economy, in: Rigling, A., Schaffer, H.P. (Eds.), *Forest Report 2015.*  
981 *Condition and Use of Swiss Forests.* Federal Office for the Environment (FOEN), Bern, Swiss Federal  
982 Institute for Forest Snow and Landscape Research (WSL), Birmensdorf, pp. 98-99.
- 983 Thom, D., Rammer, W., Dirnböck, T., Müller, J., Kobler, J., Katzensteiner, K., Helm, N., Seidl, R., 2017.  
984 The impacts of climate change and disturbance on spatio-temporal trajectories of biodiversity in a  
985 temperate forest landscape. *Journal of Applied Ecology* 54, 28-38.
- 986 Thürig, E., Kaufmann, E., 2010. Increasing carbon sinks through forest management: a model-based  
987 comparison for Switzerland with its Eastern Plateau and Eastern Alps. *European Journal of Forest  
988 Research* 129, 563-572.
- 989 Thürig, E., Palosuo, T., Bucher, J., Kaufmann, E., 2005. The impact of windthrow on carbon  
990 sequestration in Switzerland: a model-based assessment. *Forest Ecology and Management* 210, 337-  
991 350.
- 992 Uhde, B., Andreas Hahn, W., Griess, V.C., Knoke, T., 2015. Hybrid MCDA Methods to Integrate  
993 Multiple Ecosystem Services in Forest Management Planning: A Critical Review. *Environmental  
994 Management* 56, 373-388.
- 995 van der Plas, F., Manning, P., Soliveres, S., Allan, E., Scherer-Lorenzen, M., Verheyen, K., Wirth, C.,  
996 Zavala, M.A., Ampoorter, E., Baeten, L., Barbaro, L., Bauhus, J., Benavides, R., Benneter, A., Bonal, D.,  
997 Bouriaud, O., Bruelheide, H., Bussotti, F., Carnol, M., Castagneyrol, B., Charbonnier, Y., Coomes, D.A.,  
998 Coppi, A., Bastias, C.C., Dawud, S.M., De Wandeler, H., Domisch, T., Finér, L., Gessler, A., Granier, A.,  
999 Grossiord, C., Guyot, V., Hättenschwiler, S., Jactel, H., Jaroszewicz, B., Joly, F.-x., Jucker, T., Koricheva,

- 1000 J., Milligan, H., Mueller, S., Muys, B., Nguyen, D., Pollastrini, M., Ratcliffe, S., Raulund-Rasmussen, K.,  
1001 Selvi, F., Stenlid, J., Valladares, F., Vesterdal, L., Zielínski, D., Fischer, M., 2016. Biotic homogenization  
1002 can decrease landscape-scale forest multifunctionality. *Proceedings of the National Academy of*  
1003 *Sciences* 113, 3557.
- 1004 Verkerk, P.J., Zanchi, G., Lindner, M., 2014. Trade-offs between forest protection and wood supply in  
1005 Europe. *Environmental Management* 53, 1085-1094.
- 1006 Werner, F., Taverna, R., Hofer, P., Richter, K., 2005. Carbon pool and substitution effects of an  
1007 increased use of wood in buildings in Switzerland: first estimates. *Ann. For. Sci.* 62, 889-902.
- 1008 Werner, F., Taverna, R., Hofer, P., Thürig, E., Kaufmann, E., 2010. National and global greenhouse gas  
1009 dynamics of different forest management and wood use scenarios: a model-based assessment.  
1010 *Environmental Science & Policy* 13, 72-85.
- 1011 Wolfslehner, B., Seidl, R., 2010. Harnessing ecosystem models and multi-criteria decision analysis for  
1012 the support of forest management. *Environmental Management* 46, 850-861.
- 1013 Wördehoff, R., 2016. Kohlenstoffspeicherung als Teilziel der strategischen Waldbauplanung erläutert  
1014 an Reinbeständen verschiedener Baumarten in Niedersachsen, Fakultät für Forstwissenschaften und  
1015 Waldökologie. Georg-August-Universität Göttingen, Göttingen, p. 190.
- 1016 Wördehoff, R., Spellmann, H., Evers, J., Nagel, J., 2011. Kohlenstoffstudie Forst und Holz  
1017 Niedersachsen. Göttingen : Universitätsverlag Göttingen.
- 1018 Zanchi, G., Belyazid, S., Akselsson, C., Yu, L., 2014. Modelling the effects of management  
1019 intensification on multiple forest services: A Swedish case study. *Ecological Modelling* 284, 48-59.
- 1020 Zell, J., Rohner, B., Thürig, E., Stadelmann, G., 2019. Modeling ingrowth for empirical forest  
1021 prediction systems. *Forest Ecology and Management* 433, 771-779.
- 1022