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Trade-offs between ecosystem service provision and the predisposition to disturbances: a NFI-based scenario analysis

Christian Temperli[1*], Clemens Blattert[1,2], Golo Stadelmann[1], Urs-Beat Brändli[1] and Esther Thürig[1]

Abstract

Background: Scenario analyses that evaluate management effects on the long-term provision and sustainability of forest ecosystem services and biodiversity (ESB) also need to account for disturbances. The objectives of this study were to reveal potential trade-offs and synergies between ESB provision and disturbance predisposition at the scale of a whole country.

Methods: The empirical scenario model MASSIMO was used to simulate forest development and management from years 2016 to 2106 on 5086 sample plots of the Swiss National Forest Inventory (NFI). We included a business-as-usual (BAU) scenario and four scenarios of increased timber harvesting. Model output was evaluated with indicators for 1) ESB provision including a) timber production, b) old-growth forest characteristics as biodiversity proxies and c) protection against rockfall and avalanches and 2) for a) storm and b) bark beetle predisposition.

Results: The predisposition indicators corresponded well (AUC: 0.71–0.86) to storm and insect (mostly bark beetle) damage observations in logistic regression models. Increased timber production was generally accompanied with decreased predisposition (storm: >−11%, beetle: >−37%, depending on region and scenario), except for a scenario that promoted conifers where beetle predisposition increased (e.g. + 61% in the Southern Alps). Decreased disturbance predisposition and decreases in old-growth forest indicators in scenarios of increased timber production revealed a trade-off situation. In contrast, growing stock increased under BAU management along with a reduction in conifer proportions, resulting in a reduction of beetle predisposition that in turn was accompanied by increasing old-growth forest indicators. Disturbance predisposition was elevated in NFI plots with high avalanche and rockfall protection value.

Conclusions: By evaluating ESB and disturbance predisposition based on single-tree data at a national scale we bridged a gap between detailed, stand-scale assessments and broader inventory-based approaches at the national scale. We discuss the limitations of the indicator framework and advocate for future amendments that include climate-sensitive forest development and disturbance modelling to strengthen decision making in national forest policy making.

Keywords: Disturbance, Ecosystem services, Empirical model, Forest inventory, Scenario analysis

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* Correspondence: christian.temperli@wsl.ch
[1]Swiss Federal Institute for Forest, Snow and Landscape Research WSL, 8903 Birmensdorf, Switzerland
Full list of author information is available at the end of the article

Introduction

Forests benefit human wellbeing by providing ecosystem services such as timber, the regulation of water, carbon and nutrient fluxes and opportunities for recreation (Millenium Ecosystem Assessment 2005). Forests also support high biodiversity levels, which ensures forest resilience and is of high value in itself (Oliver et al. 2015). Evaluations of the effects of management scenarios on the sustainable provision of forest ecosystem services and biodiversity (ESB) need to account for levels of ESB provision, trade-offs between individual ESB (Eggers et al. 2017) and also the ability of forests to deliver ESB continuously over long time periods (Albrich et al. 2018). Disturbance events such as wind storms and bark beetle calamities may disrupt the continuity in ESB provision (Schelhaas et al. 2003; Thom and Seidl 2016). The frequency and extent of such large-scale disturbances have increased over the past decades and are projected to do so further under climate change scenarios (Seidl et al. 2011). Disturbances may damage valuable standing timber (Seidl et al. 2008; Peltola et al. 2010) and affect forest biodiversity either positively by creating habitat diversity or negatively by reducing late-seral successional stages (Thom and Seidl 2016; Hilmers et al. 2018). A principal goal in the management of protection forests is to prevent disturbances in order to maintain a continuous forest cover that is capable of preventing rock fall and the origination of snow avalanches (Brang et al. 2008). Forest management for continuous ESB provision needs to aim for tree species mixtures and stand structures that minimize the predisposition of forests to disturbances (Gardiner and Quine 2000; Yousefpour et al. 2017). Hence, scenarios of potential future forest management have to be evaluated with regard to the effects on ESB provision as well as on the forest's predisposition to disturbances.

Previous assessments of management effects on ESB provision that were based on forest development models have accounted for disturbances such as windthrow and bark beetles at the level of stands and management units (Temperli et al. 2012; Maroschek et al. 2014; Thom and Seidl 2016; Cantarello et al. 2017; Irauschek et al. 2017). However, inventory-based assessments representative for a whole region or country have rarely evaluated forest management scenarios with respect to both ESB provision and disturbance risks (Gutsch et al. 2018; Huang et al. 2018; Jandl et al. 2018). In particular, potential trade-offs and synergies between ESB provision and disturbance risks under national forest management policies have so far not been investigated at the national scale.

National policies and previous assessments of potential future timber availability in several Central European countries, including Switzerland, consider scenarios of increased timber harvesting. The goal is to promote local wood use as a CO_2-neutral construction material and source of energy and to therewith support local forest industry, sequester carbon and substitute fossil fuels (Federal Office for the Environment FOEN 2013; Nabuurs et al. 2015; Stadelmann et al. 2016; Jandl et al. 2018). These "climate-smart" forest management policies contrast with recent developments of increasing growing stocks in poorly accessible mountain regions where profitable commercial logging is difficult due to high harvesting costs (Brändli and Röösli 2015; Taverna et al. 2016; Yousefpour et al. 2018). Governmentally incentivized protection forest management, however, has shown to be a strong driver of potential future timber yields in mountain regions (Temperli et al. 2017a). At well accessible sites at lower elevations, further increases in timber yield may have to be balanced with the retention of habitat trees and other old-growth forest structures (Temperli et al. 2017b). However, these assessments did not account for potential effects of increasing growing stocks or, in contrast, policies to increase timber yield on disturbance risks and how they may trade-off with forest ecosystem services and biodiversity provision.

Policies that promote increased timber yield result in shorter cutting cycles and rotations, a lower abundance of old, large and susceptible trees and thus a putatively lower predisposition to wind and bark beetle disturbances (Dobbertin 2002; Netherer 2003). In contrast, increased harvesting may reduce biodiversity by diminishing structurally diverse patches of old-growth forests with high deadwood volumes and high densities of large and old trees that provide micro habitats for a broad range of cavity-nesting and saproxylic organisms (Winter and Möller 2008; Rosenvald et al. 2011). Protection against gravitational hazards generally increases with stand density and tree diameter (Berger and Dorren 2007) and so does predisposition to storm and bark beetle disturbances. Hence, protection forest management requires balancing present protection efficacy with disturbance predisposition and thus protection in the future (Brang et al. 2008).

The objective of this study was to reveal potential antagonistic (trade-off) and synergistic relationships between ESB provision and disturbance predisposition for the forest area of Switzerland. We used data from the Swiss National Forest Inventory (NFI) and tree-level output data from the NFI-based forest development model MASSIMO to calculate ecosystem service provision and disturbance predisposition. MASSIMO was applied in a previous project to predict growing stock, increment and potential timber harvests under business as usual (BAU) management and four scenarios of increased timber harvests (Stadelmann et al. 2016). Specifically, we asked: 1) does increasing timber yield trade-off with disturbance predisposition? 2) How do BAU management and increased timber yield affect old-growth forest features and are there trade-offs and synergies with disturbance predisposition? 3) How does disturbance predisposition relate to protection against rockfall and avalanches?

Material and methods

Study area and data

The study area was confined to the forest area of Switzerland of 1.31 million ha (Brändli and Röösli 2015) and is based on data of the Swiss National Forest Inventory (NFI), of which to date three complete and one partial (re-) measurement cycle(s) are published: NFI1 1983/85, NFI2 1993/95, NFI3 2004/06 and NFI4b 2009/13 (Abegg et al. 2014a; Traub et al. 2017). The 1 km sampling grid of NFI1 encompassed 10,981 sample plots and the 1.44 km grid of NFI2, NFI3 and NFI4b encompassed 6412, 6608 and 3376 sample plots (Abegg et al. 2014b). The model simulations by Stadelmann et al. (2016), on which this study builds, were initialized with data from the 5086 sample plots that have been resampled both in NFI2 and NF3 (Fig. 1). On each sample plot, trees ≥12 cm in diameter at breast height (DBH) were recorded on a 200 m^2 circle, trees ≥36 cm DBH on a 500 m^2 concentric circle and young trees < 12 cm DBH and ≥10 cm in height in two 14 m^2 satellite plots (Stierlin and Zinggeler 2001; Lanz et al. 2016). The Swiss NFI differentiates five biogeographically and socio-economically distinct so-called production regions: Jura, Plateau, Pre-Alps, Alps, Southern Alps (Fig. 1).

Low-elevation (< 600 m a.s.l.) forests in Switzerland are naturally dominated by beech (*Fagus sylvatica* L.) with the proportion of fir (*Abies alba* M.) increasing towards higher elevations. Montane spruce- (*Picea abies* L.) fir forest and subalpine spruce forests dominate at the northern slope of the Alps, while stone pine- (*Pinus cembra* L.) larch (*Larix decidua* M.) forests form the tree-line in the central Alps. Scots pine (*Pinus silvestris* L.) and mountain pine (*Pinus mugo* T.) forests are common in the central Alpine valleys and the lower elevations of the southern slope of the Alps is dominated by mixed deciduous forests (Cioldi et al. 2010). Forests in Switzerland are heavily influenced by past management that favored conifers predominantly in the Jura, the Plateau and in the Pre-Alps such that 62% of the Swiss forest area is covered by conifer forests (> 50% basal area) by today. Recent changes in management reduced the area covered by pure conifer forests (> 90% basal area) by 8% since 1985 (Brändli and Röösli 2015).

Modeling forest development

We used the output data of simulations that Stadelmann et al. (2016) generated with the empirical individual-tree model MASSIMO to assess timber supply under potential future harvesting scenarios (Thürig and Kaufmann 2010; Stadelmann et al. 2019). MASSIMO can be used to project the growth (basal area increment, BAI), regeneration, mortality and management of trees in 10-year time steps on the 500 m^2 sample plots of the Swiss NFI. Tree species-specific BAI depends on diameter, basal area, basal area of larger trees, stand age, dominant

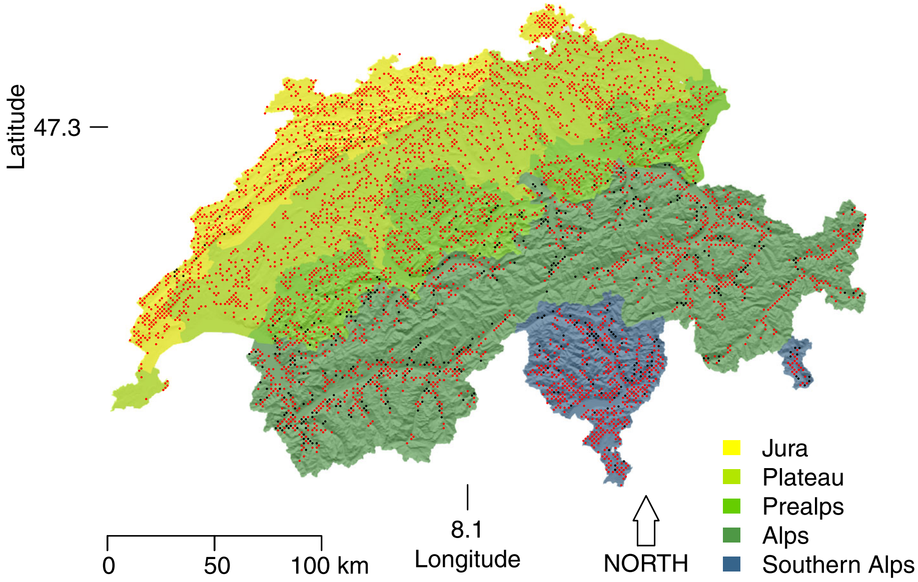

Fig. 1 Location of the 5086 NFI sample plots (red and black dots) that were used in this study in Switzerland. The color shading shows the borders of the five production regions. Sample plots in black are located within the SilvaProtect perimeter for forests that protect against avalanches and rockfall. Note that this perimeter does not include protection forests against landslides

DBH, site index, elevation above sea level and accounts for a growth release following management interventions (Thürig et al. 2005a). Density-dependent (self-thinning) and windthrow-induced mortality is simulated based on observed probabilities (Thürig et al. 2005b). The simulation of forest management with MASSIMO comprises shelterwood cutting, thinning and regulating the conifer proportion in the regeneration. The number of sample plots treated with shelterwood cutting and thinning per decade can be adjusted to approximate user-defined growing stock or harvesting targets at the level of 15 economic regions – sub-regions of the five production regions. By default, the species composition of regenerating trees (1–12 cm DBH) follows NFI observations but can be adjusted to either favor or suppress conifers (for details see Temperli et al. 2017b). Only thinning is simulated on sample plots classified as uneven-aged to approximate continuous cover forestry. Management within the protection forests (SilvaProtect perimeter for rockfall and avalanche protection, Losey and Wehrli 2013) also excludes shelterwood cuttings to maintain a constant canopy cover. Final cuttings in mature protection forests are conducted as heavy thinning (40% basal area removal) in 30-year intervals (Temperli et al. 2017a).

Management scenarios

Stadelmann et al. (2016) developed five management scenarios with representatives of the federal office for the environment (FOEN) and stakeholders of the Conference of Cantonal Foresters, the association of Swiss forest owners, managers of large forestry enterprises, the Swiss Timber Industry Association, forest engineers and forest scientists (Table 1). These scenarios aim at reflecting current trends such as increasing growing stock in the alps and decreasing proportion of conifers in the Plateau and Jura (BAU) as well as challenges in forest policy such as high potential future demands for woody biomass and coniferous timber (e.g. energy and conifer scenarios). The conifer proportion in the regeneration was adjusted to reflect the "recommended" level as per the guidelines of NaiS (Nachhaltigkeit im Schutzwald, Frehner et al. 2005) under all scenarios except for the conifer scenario that reflected the "maximum" level. These guidelines encompass phytosociological but also silvicultural criteria. The scenarios also account for harvesting restrictions (no shelterwood cuts) in protection forests (Stadelmann et al. 2016; Temperli et al. 2017a).

In 2014, when Stadelmann et al. (2016) set up the simulations, the data from NFI2 and NFI3 were the most recent complete and consecutive NFI samples and constituted the 5086 sample plots that were used to initialize MASSIMO. To approximate forest conditions in 2016, simulated harvests in MASSIMO were iteratively adjusted until simulated growing stocks matched the most recent observations of 2013 (NFI4b). The scenarios were simulated until 2106 and replicated 20 times. Averaging across 20 replicates reduced the standard deviation of model outputs caused by the stochastic implementation of tree mortality and windthrow to an acceptable level and kept computation time feasible.

Assessment of ecosystem service and biodiversity provision

We assessed ESB provision using indicators for timber production, biodiversity and protection against rockfall and avalanches (Table 2, Blattert et al. 2017). As an index for timber production we used the yearly volume

Table 1 Management scenarios used to drive simulations of forest development with MASSIMO adapted from Stadelmann et al. (2016)

5 scenarios	Specifications and MASSIMO implementation
Business as usual (BAU)	Harvest approximated to NFI3–4b observations resulting in increasing growing stock in Jura, Pre-Alps, Alps and Southern Alps and decreasing growing stock in the Plateau.
	Recommended conifer proportion as per NaiS
Constant growing stock	Harvest is increased or decreased to maintain a constant growing stock as observed in NFI4b (2013) in all production regions.
	Recommended conifer proportion as per NaiS
High increment	Reduction of growing stock to 300 $m^3 \cdot ha^{-1}$ until 2046, then constant growing stock with the aim to increase increment in the long-term, while minimizing possible short- to medium-term reductions in increment.
	Recommended conifer proportion as per NaiS
Conifers	Promotion of conifers to meet future increases in the demand for construction wood. Reduction of growing stock to 300 $m^3 \cdot ha^{-1}$ until 2046, then increase to 300–330 $m^3 \cdot ha^{-1}$, depending on region.
	Maximum conifer proportion as per NaiS
Energy	Maximized timber production to meet the increasing demands for energy wood and wood-based chemicals. Target diameters were assumed to be little important. Growing stock reduction until 2046 to 200 $m^3 \cdot ha^{-1}$ in the Plateau, 250 $m^3 \cdot ha^{-1}$ in the Jura, the Pre-Alps, Valais, South of the Alps and 300 $m^3 \cdot ha^{-1}$ in the Alps without Valais, then constant growing stock.
	Recommended conifer proportion as per NaiS

Table 2 Indicators used to estimate ecosystem service provision

Ecosystem service	Indicator	
Timber production	Harvested stemwood within bark ($m^3 \cdot ha^{-1} \cdot y^{-1}$)	
Biodiversity	Old-growth index	Number of stems >80 DBH (per ha); Deadwood volume ($m^3 \cdot ha^{-1}$); Shannon index of basal area in 4 cm DBH classes representing structural diversity
Protection	Rockfall protection index (RPI)	
	Avalanche protection index (API)	

of harvested stemwood within bark per hectare (see definition in online glossary of the Swiss NFI, Brändli and Speich 2007). We quantified biodiversity provision by means of old-growth forest characteristics. These included the number of large trees >80 cm DBH per ha, deadwood volume and the Shannon index of basal area in 4 cm DBH classes as an index of stand structural diversity. Deadwood volume at the beginning of the simulations was summed from observed lying and standing deadwood. Decadal deadwood accumulation encompassed non-salvaged, density-dependent and windthrow-induced mortality as well as harvest residues (see Eq. 1 in Supplementary Material). Exponential decay functions specific for deciduous and coniferous and for coarse (≥7 cm) and fine deadwood accounted for deadwood decomposition (Mackensen et al. 2003; Lachat et al. 2014). We averaged the plot-level indicators and calculated standard errors to obtain estimates at the level of production regions and for Switzerland as a whole. To obtain a composite index representing the old-growth quality of the forest we scaled the regional averages of the number of large trees, the deadwood volume and the structural diversity index between their regional minimum and maximum values and averaged across the scaled components.

We used the empirical functions developed for the ROCKFORNET tool (Berger and Dorren 2007, http://www.ecorisq.org/rockfor-net-en) to estimate protection against rockfall. These functions have recently been used in a number of simulation model applications to estimate protection against rockfall in response to forest management scenarios (Cordonnier et al. 2013; Bugmann et al. 2017; Irauschek et al. 2017; Mina et al. 2017a) and have been integrated as a risk management tool in the broadly accepted NaiS recommendations for protection forest management (Dorren et al. 2015). They quantify the risk that a rock passes through a stand as a function of number of stems per ha, quadratic mean diameter (QMD) of stems, basal area per ha, the basal area ratio of conifers and broadleaves and slope angle. We assumed the mid-range values in parentheses suggested by Cordonnier et al. (2013) for the following additional variables: rock density ($2800\,kg \cdot m^{-3}$), rock volume ($1\,m^3$), the initial fall height of the rock (20 m) and the length of the slope (250 m), for which the data of the NFI sample plot with a diameter of 25.2 m are assumed to be representative. The rockfall protection index (RPI) is sensitive to these assumptions, which we accepted because the absolute values at individual sample plots were less relevant for our study than the relative effect of management.

An avalanche protection index (API) was calculated based on the ratio between the observed basal area and a reference basal area, above which avalanche release is impossible. Thereby slope angle and the conifer-broadleaf ratio are co-determinants (Cordonnier et al. 2013).

We calculated RPI and API only for sample plots within the protection forest perimeter (Fig. 1). Accounting for the left skewed distribution of both RPI and API, we obtained aggregate values across the protection forest perimeter by calculating the proportion of sample plots with high protection efficacy, i.e. with RPI and API values > 0.95.

Assessment of disturbance predisposition

We applied the predisposition assessment system (PAS) by Netherer (2003) to combine stand- and site-related indicators and expert-based weighting factors for the predisposition to storm (P_{storm}) and bark beetle (P_{beetle}) disturbance (Fig. 2). This PAS was previously applied in Austria and Switzerland (Seidl et al. 2007; Temperli et al. 2013; Jakoby et al. 2015; Jakoby et al. 2016). Stand-related indicators were derived using the measured NFI data and output from the MASSIMO simulations. We used a drought index that represents soil water balance based on available water capacity, precipitation and potential evapotranspiration as an indicator for water supply (Temperli et al. 2013). Because soil pH has shown to be a strong predictor for the probability of damage due to the storms “Lothar” and “Martin” in Switzerland, Germany and France in December 1999 (Mayer et al. 2005) we included this factor in our assessment of storm predisposition. The indicators for storm and bark beetle predisposition (*PS* and *PB*, respectively) were all scaled between 0 and 1 and combined additively. We validated the storm and bark beetle predisposition indices with records of storms Vivian (1990) and Lothar (1999) and

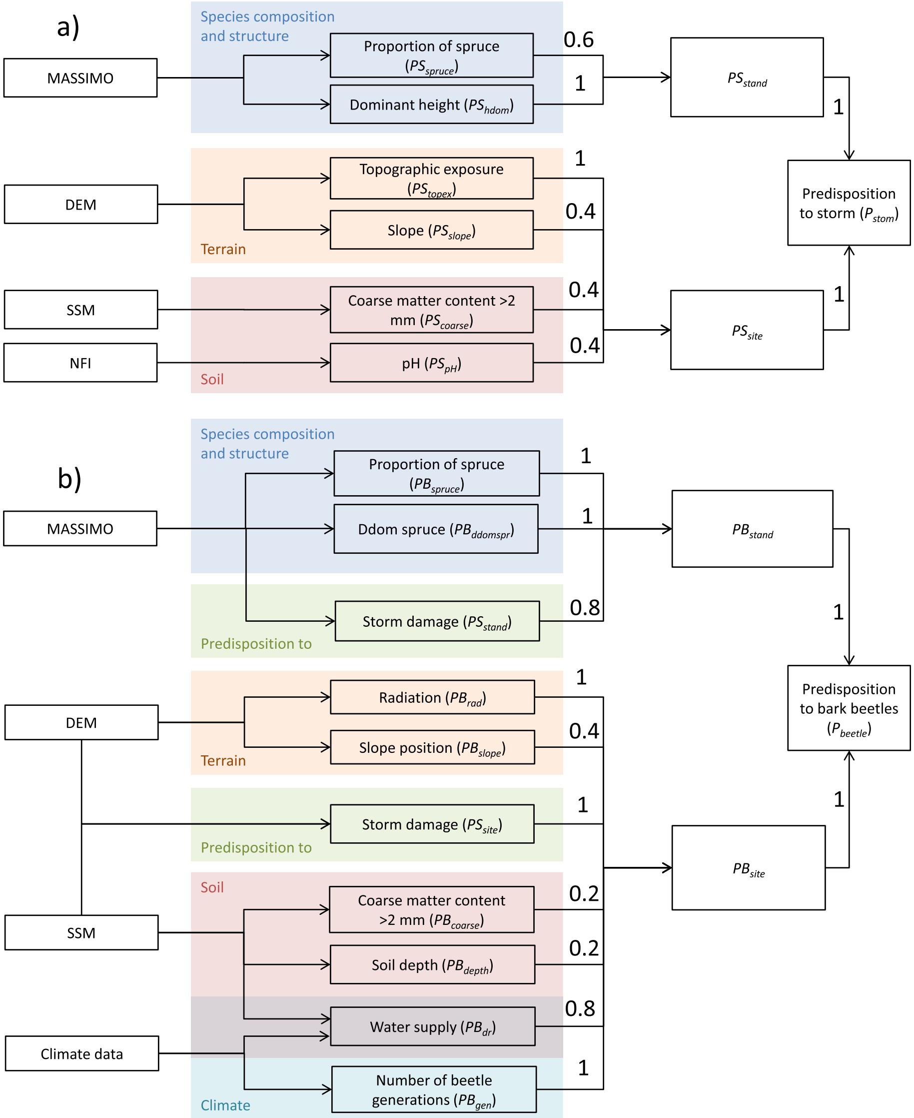

Fig. 2 Overview of storm- (*PS*) and bark beetle- (*PB*) related indicators used to assess the predisposition to storm (**a**) and bark beetle (**b**) disturbance. Indices for stand- and site-related predisposition are calculated based on output of the MASSIMO model, the digital elevation model by Swisstopo dhm25© 2018 swisstopo (5704 000000) (DEM), digital soil suitability map of Switzerland (SSM), pH measurements of the first Swiss NFI (1983/85) and gridded temperature and precipitation data for years 1982–2011 (Remund et al. 2016). Numbers on connector lines represent relative weighting factors

insect damages from NFI2 to NFI4 using logistic regression models (see details on indicator calculations and validation in Supplementary Material).

Relationship between ESB and disturbance predisposition

We quantified trade-offs and synergies between ESB provision and disturbance predisposition based on proportional changes of the ESB and predisposition estimates as compared to year 2016. These changes were calculated from the regional averages and then averaged over the simulation period (2026–2106). We defined trade-offs as those cases where ESB provision and disturbance predisposition changed in parallel (Fig. 7). A synergistic development was simulated when ESB provision increased while disturbance predisposition decreased.

Results

Validation and spatial distribution of disturbance predisposition indices

All indicators were significantly associated with either storm Vivian or Lothar or insect damage and the estimated effects were generally larger for stand-related factors than for site-related indicators (Table S2). The areas under the receiver operator curves as estimates for the discriminatory power of the logistic regression models were >0.71 (Table S3) indicating acceptable (0.7–0.8) to excellent (0.8–0.9) predictive power (Hosmer et al. 2013). We concluded from that that the predisposition indices are suitable for the evaluation of simulated forest management scenarios.

At the beginning of the simulation period in 2016, high values (>0.7) of stand-related predisposition to storm (PS_{stand}) occurred in the Pre-Alps and the Alps and site-related values were above average mainly in the western Pre-Alps where high wind exposure (PS_{topex}) prevailed (Fig. 3). High stand-related bark beetle predisposition (PB_{stand}) occurred throughout Switzerland, except where there were no spruce trees in southern Ticino and at low elevations in northern Switzerland, the Valais and the Plateau. High site-related beetle predisposition dominated at low elevations in the Plateau, southern Ticino and in the Valais where temperatures were highest and thus up to 3 generations of spruce bark beetles were possible. The combined stand- and site-related predisposition assessments reflect the requirement for both susceptible stand structure and conducive site conditions to co-occur for high predisposition. For example, the combined beetle predisposition (P_{beetle}) in high-elevation spruce forests, which are highly predisposed with respect to stand conditions, may be relatively low because of low temperatures, which inhibits the development of multiple generations. In contrast, the relatively high temperatures in the low-elevation Southern Alps may allow for up to 3 beetle generations per season, but the low availability of large spruce trees for breeding results in overall low predisposition.

Disturbance predisposition indices under management scenarios

Business-as-usual management increased storm predisposition in mountainous regions and decreased it in the Plateau (+2% in the Jura, −5% in the Plateau, +4% in the Pre-Alps, +7% in the Alps and +11% in the Southern Alps between 2016 and 2106, Fig. 4). Under the energy scenario, storm predisposition decreased by 11% in the Jura, 11% in the Plateau and 7% in the Pre-Alps by 2066 and increased again towards the end of the century. Similar developments were simulated for the high increment and the conifer scenario. Storm predisposition was strongly tied to growing stock and dominant height (Hdom), which were reduced under these scenarios until 2046 and then slowly recovered (Figs. S1 and S2).

The conifer scenario increased bark beetle predisposition by 13% for the whole of Switzerland and by 61% in the Southern Alps from 2016 to 2106 due to the increased spruce abundance (Fig. 4, Fig. S3). In other regions, beetle predisposition decreased with decreasing

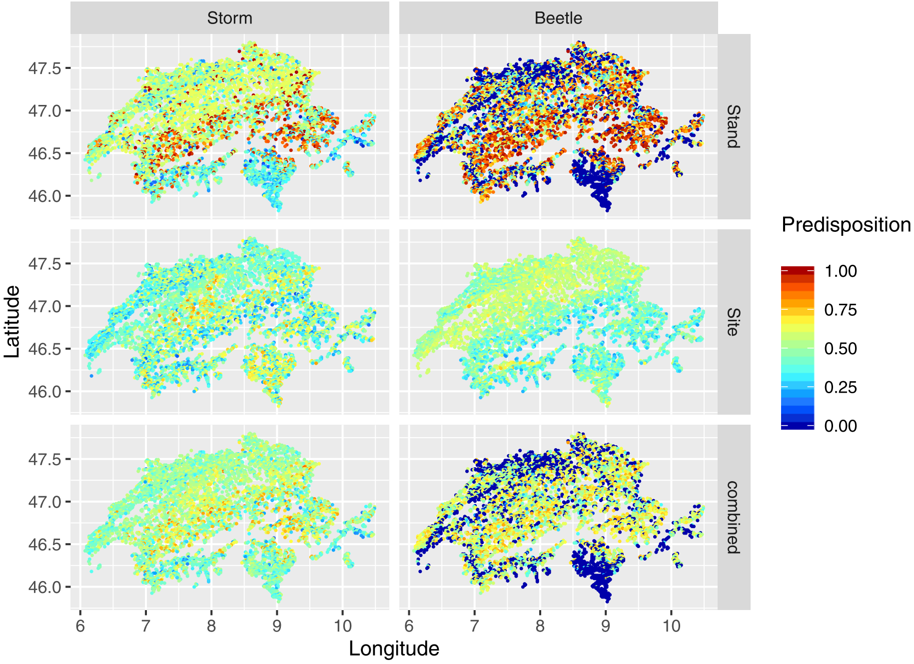

Fig. 3 Predisposition to storm (left) and bark beetle (right) disturbance in NFI sample plots at the beginning of the simulation period (2016). Top: stand-related predisposition (PS_{stand} and PB_{stand}); middle: site-related predisposition (PS_{site} and PB_{site}); bottom: combined stand- and site-related predisposition (P_{storm}, P_{beetle})

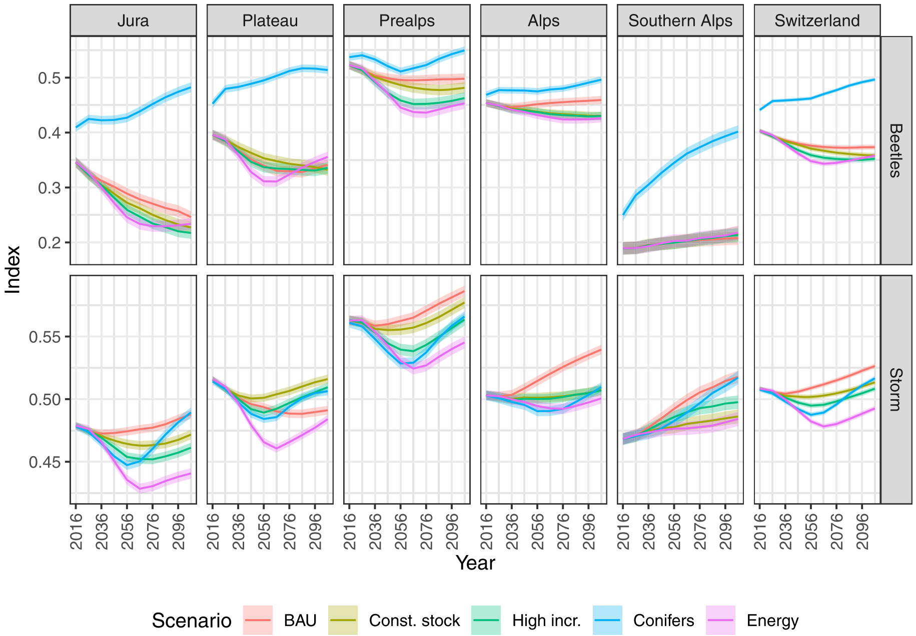

Fig. 4 Development of predisposition to bark beetles and storm disturbance by management scenario and NFI production region. Error bands indicate standard errors of means resulting from variation among NFI sample plots and scenario simulations

spruce presence (e.g. − 32% in the Jura under the Energy scenario). Increasing growing stock under BAU did not affect the beetle predisposition.

Timber harvesting and old-growth index under management scenarios

Timber harvesting was simulated in direct response to the specifications of the five management scenarios (Fig. 5). To maintain a constant growing stock, harvesting had to be decreased in the Plateau (−7% with respect to average BAU harvest from 2026 to 2106) and to be increased in the other regions (Jura: +16%, Pre-Alps: +31%, Alps: +82%, Southern Alps: +217%). The high increment, the conifer and the energy scenario resulted in harvesting to increase until 2046 in the Jura, the Plateau and the Pre-Alps (e.g., +144% under the conifer scenario in the Pre-Alps) and to drop sharply thereafter, as growing stocks were held constant (high

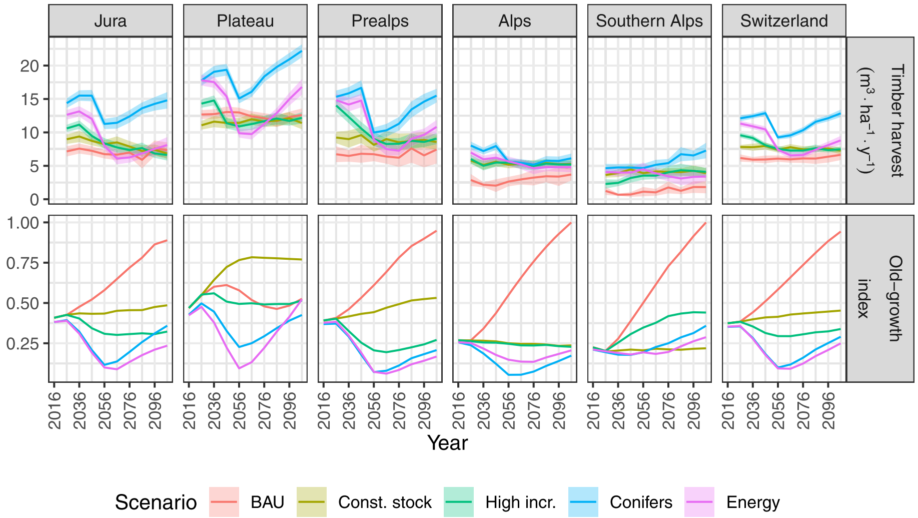

Fig. 5 Development of timber harvesting and the old-growth index by management scenario and NFI production regions. Error bands in timber harvests indicate standard errors of means resulting from variation among NFI sample plots and scenario simulations. See supplementary Fig. S4 for components of the old-growth index and their standard errors

increment and energy) or allowed to increase again (conifer). Please see Stadelmann et al. (2016) for more details.

The old-growth index increased >117% under the BAU scenario in all regions by 2106 (Fig. 5), except for the Plateau where it fluctuated and was 12% higher in 2106 than in 2016. The high harvesting intensity under the energy and the conifer scenarios reduced the old-growth index, except for the Southern Alps where it still increased, because harvesting in this region was still relatively low. Increased harvesting reduced the old-growth index due to 1) lower deadwood accumulation rate at lower growing stocks, 2) lower density of large trees and 3) lower DBH diversity when larger DBH classes are being harvested (Fig. S4).

Rockfall and avalanche protection and disturbance predisposition in protection forests

Results on rockfall and avalanche protection and their interaction with disturbance predisposition are presented separately because they are only available for the protection forest perimeter. In general, rockfall protection increased from 0.50 (i.e. 50% of sample plots were rated with a high rockfall protection efficacy > 0.95) in 2016 to 0.64 (+ 28%) in 2106 under BAU and by 11%–15% under the other scenarios. Avalanche protection decreased by 13%–20% (Fig. 6) with highest values under BAU. These developments resulted from the simulated increase in average DBH (quadratic mean diameter QMD, Fig. S5) to which rockfall protection is positively and avalanche protection negatively related (Cordonnier et al. 2013, p. 41 and 44).

Disturbance predisposition in the protection forest was neither affected by the comparably low management intensity under the BAU scenario nor the increased management intensity under the constant stock, the high increment and the energy scenarios. Only conifer promotion increased the predisposition to beetle disturbance (Fig. 6).

Trade-offs and synergies between ESB provision and disturbance predisposition

Timber production could be increased synergistically with decreasing storm predisposition if increased timber harvest reduced dominant tree height (Fig. 7a, Fig. S2). This was the case under the conifer and energy scenarios in the Jura, the Plateau, the Pre-Alps and the Alps. Even though the timber yield increased over BAU-level in the Southern Alps, it was still comparably low such that it did not decrease storm predisposition under any scenario.

We found a trade-off relationship between old-growth and storm predisposition in most situations. High-intensity management (energy and conifer) that reduced storm predisposition also reduced DBH-diversity and deadwood that contributed to the old-growth index (Fig. 7a, Fig. S4). In contrast, low intensity management that increased storm predisposition such as BAU in the Alps and the Southern Alps increased old-growth components. Exceptions from this trend were storm predisposition that decreased synergistically with increasing old-growth in the Plateau. In this region deadwood and large tree abundance increased under the constant stock, the BAU and the high increment scenarios while regional dominant tree height decreased. This paradox is likely due to a simulated shift towards a higher heterogeneity between plots with respect to stand development stages.

The development of spruce abundance determined trade-offs and synergies between timber production and beetle predisposition (Fig. 7b). Hence, we found a general trade-off between increasing timber yield through conifer promotion and increased bark beetle predisposition. However, beetle predisposition decreased, if increased timber yield was accompanied by a reduction in

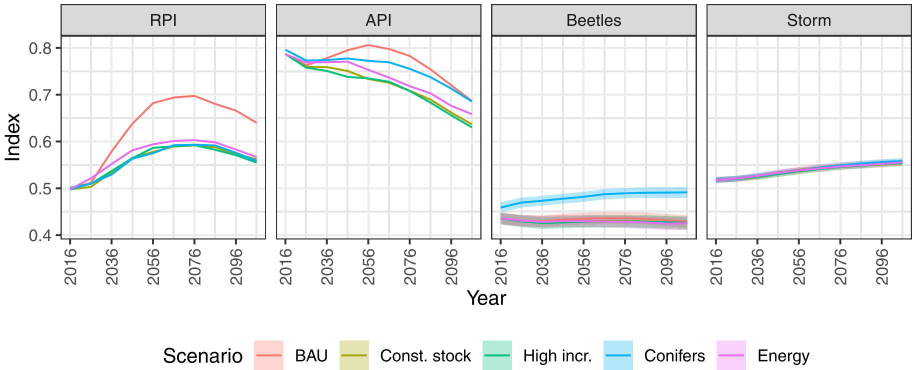

Fig. 6 Development of rockfall protection (RPI), avalanche protection (API) and storm and beetle predisposition within the protection forest perimeter (469 sample plots). Error bands in disturbance predisposition indices show standard errors of means resulting from variation among NFI sample plots and scenario simulations

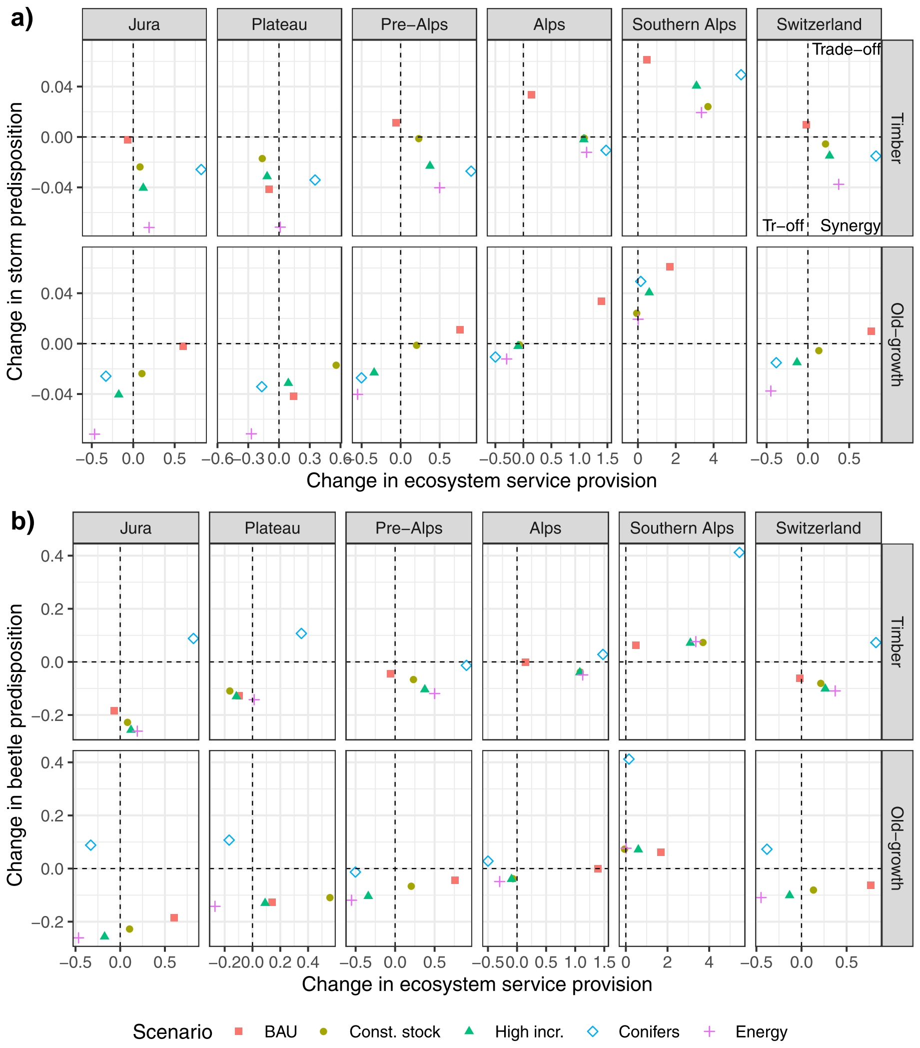

Fig. 7 Relationship between changes in storm (**a**) and bark beetle (**b**) predisposition and changes in timber harvest and old-growth index by management scenarios and region. Changes are expressed as proportional change with respect to years 2016 averaged over years 2026–2106. Note the different x-axis and y-axis scales

spruce abundance. The latter was particularly pronounced under the energy and the high increment scenario in the Jura, the Pre-Alps and the Alps but also under the conifer scenario in the Pre-Alps, where the proportion of spruce was already high in 2016 and the increased harvesting intensity reduced the predisposition to bark beetles.

Also the synergies and trade-offs between old growth and beetle predisposition were determined by the effect of management on spruce abundance. The increase in deadwood and the density of large trees together with the reduction in spruce abundance under the low-intensity constant stock and BAU scenarios in the Jura the Plateau and the Pre-Alps promoted old-growth and synergistically reduced bark beetle disturbance. The reduction in spruce abundance under the harvesting-intensive energy scenario resulted in a trade-off between decreased beetle predisposition and decreasing old-growth. The promotion of spruce under the conifer scenario resulted in the dual disadvantage of decreased old-growth and increased beetle predisposition in the Jura, the Plateau and the Alps.

Management-related trade-offs or synergies between protection and disturbance predisposition were less pronounced because the scenarios accounted for management restrictions that prevented increases in harvesting intensity under the high increment, conifer and energy scenarios in the protection forest (Fig. 6). Yet, conifer promotion increased stem numbers in comparison to the other scenarios and benefited avalanche protection (Fig. 6 and Fig. S5), which resulted in a trade-off between increased avalanche protection and increased beetle predisposition. We found a weak but significant trend (Welch's two sample t-test with $\alpha = 0.05$) towards higher storm and beetle predisposition in sample plots with high (≥0.95) rockfall and avalanche protection indices in NFI3 data (Fig. 8) and all scenario simulations (Fig. S6) indicating a general trade-off between avalanche and rockfall protection and disturbance predisposition.

Discussion

Effect of timber harvesting scenarios on disturbance predisposition

Generally, we found that scenarios of increased timber harvesting reduced disturbance predisposition. This finding has been documented previously (Hood et al. 2016) and shown in other modeling studies (Gustafson et al. 2004; Albrecht et al. 2012). It may be applicable to wind disturbance at a regional scale as increased timber harvesting reduces the abundance of large and unstable trees (Dobbertin 2002) and thus the risk of loss of valuable timber (Loisel 2014), but it cannot be readily transferred to the stand scale. Thinning may expose vulnerable trees and increase the risk to windthrow (Valinger and Fridman 2011). Vice-versa, BAU increased growing stock and dominant tree heights throughout Switzerland except for the Plateau with the consequential increase in the predisposition to storm disturbance. This scenario is congruent with the increasing growing stock in the past decades in many regions across Europe, which contributed together with climate change to the currently higher observed disturbance damages (Seidl et al. 2011).

Spruce presence and thus the predisposition to bark beetle disturbance decreased in the Jura, the Plateau and to some degree in the Pre-Alps under the scenarios of increased timber harvesting. The reason for this was the lower proportion of spruce in the simulated regeneration than in the NFI3 data MASSIMO was initialized with. This, in turn, is congruent with the long-term trend observed in the NFI of decreased conifer proportions at lower elevations, i.e. outside the natural distribution range of Norway spruce (Brändli and Abegg 2009). Policies to increase timber mobilization will likely accelerate this trend (Temperli et al. 2017a). Promoting Norway spruce as a valuable timber resource together with increased harvesting as under our conifer scenario obviously reversed the effect and contradicts with management recommendations to decrease the risk for bark beetle disturbance (Vacchiano et al. 2013).

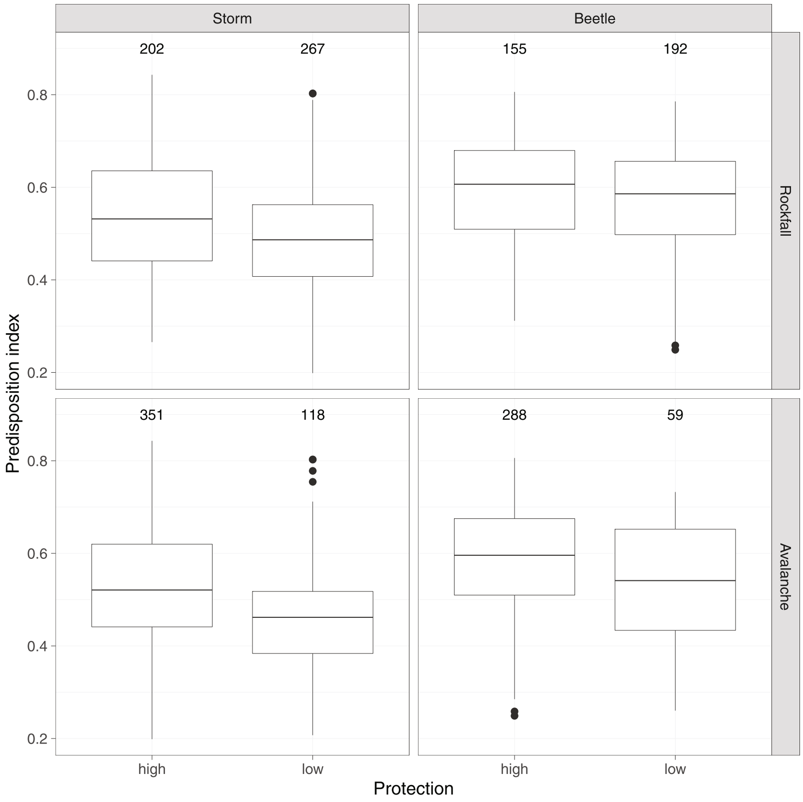

Fig. 8 Boxplots of storm (left panels) and bark beetle (right panels) predisposition in NFI3 sample plots within the protection forest perimeter. Sample plots were classified by high (≥ 0.95) and low rockfall (top panels) and avalanche (bottom panels) protection. The number of sample plots is shown on top of boxplots. Only the 347 out of 469 sample plots that contained spruce trees were used to display beetle predisposition

Old-growth characteristics and disturbance predisposition

We found management that reduces predisposition to storm disturbance to also reduce old-growth forest characteristics that are typical of rare late-seral development stages (Svoboda and Pouska 2008). This finding collides with a large body of literature that found disturbances to positively affect forest biodiversity mainly by creating structural diversity, heterogeneity in stand development classes (patchiness) and thus reducing intra-specific competition (Bouget and Duelli 2004; Lehnert et al. 2013; Thom and Seidl 2016). However, the indicators used here have to be interpreted as proxies of habitat suitability for taxa such as cavity-nesting birds and mammals and saproxylic fungi and insects that depend on late-seral development stages (Rosenvald et al. 2011). They cannot be regarded as indicators for general biodiversity and are thus not directly comparable to the indicator sets used in the above mentioned studies.

To assess the effects of natural disturbances and management on tree diversity one would have to account for disturbance- and management-induced changes in environmental conditions (i.e. light and nutrient availability) that in turn control the species composition of regenerating trees (Rammig et al. 2007). This was not possible with this version of MASSIMO, but current revisions of the model that focus on regeneration will allow accounting for such effects (Zell et al. 2019). Including indicators that account for management- and disturbance-induced changes in habitat suitability of management- and disturbance-sensitive umbrella species may improve our assessment of biodiversity provision (Lexer and Seidl 2009; Mikoláš et al. 2017).

Our results illustrate how management for old-growth characteristics can synergistically decrease the predisposition to bark beetle disturbance if the abundance of Norway spruce is reduced concomitantly. While this may just proof the obvious it also points out the dual benefit of low-intensity management in conjunction with natural (broadleaves dominated) regeneration (Jactel et al. 2009). In contrast, a reduction of beetle predisposition with more intensive management as under our energy scenario, was in a trade-off relationship with reduced old-growth features. Previous studies have shown positive effects of beetle disturbance on forest species diversity in the Bavarian forest and the Carpathians, due to increased stand structural diversity (Lehnert et al. 2013; Mikoláš et al. 2017). Others found host dilution with increased tree diversity to increase Engelmann spruce survival in spruce beetle affected forests in western North America (Conner et al. 2014). Together with our results, these studies suggest that there are various ways to realize synergies between the prevention of bark beetle disturbance and the promotion of biodiversity. Ideally they are combined to generate landscape heterogeneity and thus a broad range of different habitats on a small area, i.e. by promoting old-growth patches of non-host species (Bouget et al. 2014) and by timber harvesting that emulates patch-scale natural disturbances (Mikoláš et al. 2015, 2017).

Protection and disturbance predisposition

The average disturbance predisposition in sample plots with high (>0.95) avalanche and rockfall protection value was slightly but significantly higher than in sample plots with lower protection value both during NFI3 (Fig. 8) and in scenario simulations (Fig. S6). As such, these results underpin previous simulation studies that found a trade-off between the temporal stability and the level of protection (Cordonnier et al. 2008; Albrich et al. 2018). The here used protection indicators (RPI and API) suggest high protection efficacy for dense and mature spruce forest that in turn lack long-term stability (Brang et al. 2004). However, these protection indicators do not account for the effect of downed stems and stumps on the protection efficacy against avalanches and rockfall (Krumm et al. 2011; Fuhr et al. 2015). Mature forests that are affected by patch-scale disturbance may indeed sustain the protection function due to such deadwood, at least as long as the downed logs remain in early decay stages and if advanced regeneration is present to replace the downed trees (Amman 2006). Further research is necessary to quantify these effects such that they can be included in a modeling and indicator framework such as the one presented here.

Analysis approach

By initializing model projections with single-tree data from the Swiss NFI we fully represented the range of forest compositional and stand structural types in Switzerland. A similar framework to reveal trade-offs between forest ecosystem services was presented by Gutsch et al. (2018) and involved a process-based forest development model that was initialized with aggregated German NFI data. Regional or even continental studies are often forced to a rather coarse representation of forest management and ecosystem service provision. Recent examples are assessments that found fire and bark beetle disturbances to diminish carbon sequestration under climate change (Seidl et al. 2014; Ghimire et al. 2015). In contrast, studies that used detailed indicators on ESB provision and accurately depicted forest management in assessments of interactions between disturbances and ESB are restricted to stands or comparably small case study landscapes (Maroschek et al. 2014; Albrich et al. 2018). The here presented approach bridges this gap by combining representative forest development modeling at the national-scale with a detailed implementation of forest management and single tree-based quantification of disturbance predisposition and ecosystem service provision.

The MASSIMO simulations by Stadelmann et al. (2016), that were used for the analyses in this study, included storm-induced tree mortality, the probability of which differed regionally and was calculated as a function of dominant diameter, conifer proportion and stand structure (uneven-aged vs. even-aged) (Thürig et al. 2005b; Stadelmann et al. 2019). These are similar parameters as those used as indicators for stand-related storm predisposition. Hence, the simulated storm-induced tree mortality was elevated in sample plots with high storm predisposition. This in turn may have dampened the effects of the management scenarios on the storm predisposition indicators and thus hampers comparisons between storm and bark beetle predisposition. Nevertheless, the relative effects of the scenarios as well as the trade-off relationships with the ESB indicators that are the scope of this study were not affected by the simulation of storm-induced tree mortality.

The simulations did not account for the effects of climate change. Projected increased temperatures and decreased summer precipitation (CH2018 2018) will likely increase the predisposition of spruce forests to bark beetle damages (Temperli et al. 2013). Ensembles of global climate projections indicate increased storm frequency and intensity for central Europe (Pardowitz 2015). Together with the direct effect of climate change, disturbance-mediated changes will likely favor beech and oak at the expense of Norway spruce at low to mid elevations potentially leading to novel species associations (Thom et al. 2017). Increased disturbance activity and a shift towards deciduous tree species may benefit forest biodiversity via increased deadwood and structural complexity but may be detrimental for species depending on old-growth forest structures (Thom and Seidl 2016). Increased disturbance activities endanger the stability of protection forests (Maroschek et al. 2014), but in the longer term the increased share of deciduous species with high wood densities may also benefit protection against rockfall (Perzl 2006). Further development in MASSIMO needs to focus on climate-sensitive tree growth, regeneration and mortality, and dynamic storm and bark beetle disturbance sub-models that integrate the here used predisposition indicators (Mina et al. 2017b; Rohner et al. 2018; Zell et al. 2019). This will allow to fully account for climate change- and disturbance-induced shifts in tree regeneration, growth and mortality, and will enable investigations on the effects of forest management on disturbance regimes and associated ramifications for ESB provision.

The evaluation of MASSIMO output with indicators on disturbance predisposition and ecosystem services revealed strengths and deficiencies of both the MASSIMIO model and the indicator framework. Average stem number decreased from 564 stems·ha^{-1} to 378–464 stems·ha^{-1} in the course of the simulations in the protection forest and the quadratic mean diameter increased from 34 cm to 45–47 cm, which also explains the curved basal area development (Fig. S5). This indicates insufficient simulated regeneration to sustain a stable DBH and age structure, which is the very goal of protection forest management (Brang et al. 2008). MASSIMO aims at maintaining stand stability in the protection forest by omitting shelterwood cutting *in lieu* of a relatively intense but infrequent thinning regime. However, it fails in doing so by omitting the simulation of increased regeneration following the heavy thinning. Future implementations of protection forest management in MASSIMO should remedy this deficiency and account for the regeneration response to increased light-availability following heavy thinning.

We here used protection indices that have originally been developed to assess the protection efficacy of individual stands. The rockfall protection index accounts besides stand structural parameters also for rock dimension, initial fall height, forested and un-forested slope length and inclination (Berger and Dorren 2007). While the statistical models have been validated over a wide range of forest and stand structural types, it remains to be tested how they perform with output of forest models as in this and previous studies (Irauschek et al. 2017; Mina et al. 2017a), where assumptions on rock dimensions, initial falls height and slope length had to be made. The avalanche protection index as used here and in a number of previous studies does not account for canopy gaps even though they are important for avalanche release (Cordonnier et al. 2013). Whether such gaps are accounted for by aggregating over many NFI sample plots also requires further investigation. Consequently, the absolute values of the protection indices need to be interpreted with caution, and only the effect of (management-induced) changes in stand structure and composition in relation to a reference situation (here year 2016) can be reliably assessed and interpreted. Alternatively, the indicators for rockfall and avalanche protection that Elkin et al. (2013) and Schuler et al. (2016) used may be applied to NFI and MASSIMO output data. These indicators only account for stand structural parameters and may thus be less precise. However, they may be easier to interpret due to their simplicity. It remains to be tested whether they depict the general relationships between stand composition and structure and protection efficacy more transparently and thus may be better suited to reveal causal relationships in a large-scale, long-term modeling application as this.

Climate change may also change the demand for protection. Avalanche release zones may shift upslope (Schmucki et al. 2017), and permafrost thawing may increase rockfall (Gruber and Haeberli 2007). Our simulation results need to be interpreted in the context of these potential changes.

Implications for management and policy making

The evaluation of the five timber harvesting scenarios indicated that increased timber yield in disturbance prone areas may forestall potential future disturbance damages and may support the adaptation of the species composition towards a more resilient state (DeRose and Long 2014; Brang et al. 2016). This however requires seed trees or planting of climate change-adapted species and suitable conditions for rapid tree establishment. Ensuring a high potential for climate change-adapted tree species to establish thus entails fostering a diverse set of tree species including those that unfold their full growth potential only under anticipated future conditions (Yachi and Loreau 1999; Morin et al. 2014).

The conifer scenario highlighted the trade-off between timber harvesting and predisposition to bark beetle disturbance, with spruce abundance being the obvious driver of beetle predisposition. In the light of currently ongoing wide spread drought and beetle-induced spruce mortality in central Europe (e.g. Stroheker et al. 2020) and with climate change likely aggravating the situation (Temperli et al. 2013), the conversion of spruce forests outside of their natural distribution range towards a more drought and disturbance resistant species composition should be a top priority for forest policy and management (Yousefpour and Hanewinkel 2014).

For remote and poorly accessible forests without protective function, passive management that involves accepting damages due to disturbances may be a realistic scenario. Such a cessation of active management is currently practiced in many parts of the Alps, particularly at its southern slopes even though national forest policy aims at a sustainable exploitation of harvestable timber (Federal Office for the Environment FOEN 2013). In addition to the reduced management costs such a scenario may also support biodiversity via increased abundance of old-growth structures, deadwood and disturbance-induced gap dynamics and landscape heterogeneity (Lassauce et al. 2011).

Conclusions

This study presents a simulation modeling framework based on forest inventory data that allows assessing consequences of forest management scenarios on ecosystem service and biodiversity (ESB) provision and disturbance predisposition on a national scale. We found that the effect on dominant tree height and spruce abundance was most decisive of how management for ecosystem services affected disturbance predisposition. Increased timber harvesting that reduced the abundance of large trees reduced the predisposition to storm disturbance and promoting conifers to increase timber production increased the predisposition to bark beetle disturbance. Promoting old-growth characteristics was in a trade-off relationship with preventing storm disturbance but could be in synergy with reducing beetle predisposition in lower elevation regions. Our results also indicate that protection against avalanches and rockfall needs to be balanced against disturbance risks. By evaluating ESB and disturbance predisposition based on single-tree NFI data at a national scale we bridged a gap between detailed, process-based assessments at the stand-scale and inventory-based approaches at the national scale.

Quantifying ESB and disturbance predisposition concomitantly using NFI-based scenario modelling allows identifying management goals and restrictions, environmental conditions and legacies of past management under which ESB can be provided sustainably over long time frames. This is particularly relevant for national forest policy making to detect potentially colliding goals and to identify priority areas for disturbance prevention and the provision of ecosystem services.

Supplementary information

Supplementary information accompanies this paper at https://doi.org/10.1186/s40663-020-00236-1.

Additional file 1: Supplementary material.

Abbreviations

API: Avalanche protection index; AUC: Area under the receiver operator curve; BAI: Basal area increment; BAU: Business as usual; DBH: Diameter at breast height; ESB: Ecosystem services and biodiversity; Hdom: Dominant height; MASSIMO: Management scenario simulation model; MLRM: Multiple logistic regression model; NFI: National forest inventory; NaiS: Nachhaltigkeit im Schutzwald (Sustainability in protection forests); PAS: Predisposition assessment system; QMD: Quadratic mean diameter; RPI: Rockfall protection index; SLRM: Single variable regression model; TPR: True positive rate

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Authors' contributions

CT and CB conceived the research, GS and ET performed MASSIMO simulations, CT and CB analyzed and interpreted MASSIMO output with respect to ecosystem service provision and disturbance predisposition, CT wrote the initial draft of the manuscript and all authors commented, edited and approved the final version of the manuscript.

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Availability of data and materials

The data of the Swiss National Forest Inventory (NFI) that has been used to initialize MASSIMO model simulations are available from the NFI database (NAFIDAS) system within the scope of a contractual agreement (Please see https://www.lfi.ch/dienstleist/daten-en.php?lang=en, accessed 30 July 2019). Aggregated MASSIMO simulation data are available from the corresponding author on reasonable request.

Compliance with ethical standards

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

Author details

[1]Swiss Federal Institute for Forest, Snow and Landscape Research WSL, 8903 Birmensdorf, Switzerland. [2]University of Jyväskylä, FI-40014 Jyväskylä, Finland.

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