European Journal of Forest Research (2020) 139:483–498
https://doi.org/10.1007/s10342-020-01263-x

ORIGINAL PAPER

Climate change impacts across a large forest enterprise in the Northern Pre-Alps: dynamic forest modelling as a tool for decision support

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Received: 20 August 2019 / Revised: 29 January 2020 / Accepted: 4 February 2020 / Published online: 6 March 2020

Abstract

Mountain forest managers face the challenge to anticipate climate change (CC) impacts across large elevational ranges. For management planning, information on site-specific long-term responses to CC as well as the consequences for protection functions is particularly crucial. We used the process-based model ForClim to provide projections of forest development and their protective function as decision support for a large forest enterprise in the Northern Pre-Alps. Specifically, we investigated the impact of three climate scenarios (present climate, low- and high-impact CC) at five representative sites along an elevational gradient (700–1450 m a.s.l.). Relatively small changes to current forest structure and composition were evident under present climate, but divergent trajectories occurred under CC: while the low-elevation sites (≤ 1000 m) were affected by drought-related mortality, high-elevation sites benefited from the warming. Changes at low-elevation sites were accompanied by shifts in species composition, favouring in particular *Tilia* ('low-impact' CC) and *Pinus sylvestris* ('high-impact' CC). Forest management accelerated the shift towards climate-adapted tree species, thereby reducing detrimental effects of the 'low-impact' CC scenario. Under the 'high-impact' scenario, however, drastic decreases in protective function occurred for the late twenty-first century at low elevations. A set of exemplary disturbance scenarios (windthrow and bark beetle) demonstrated the importance of forest management and low browsing for the resilience of mountain forests. Overall, our results underline the potential of process-based forest models as decision support tools for forest enterprises, providing local projections of CC impacts across large elevational ranges at the site-specific resolution required by forest managers.

Keywords Mountain forest · Climate change impacts · Switzerland · Dynamic vegetation model · Ungulate browsing

Introduction

The increasing impacts of climate change on forests worldwide (e.g. Allen et al. 2010) have brought forest managers in the difficult position to balance multiple demands for forest ecosystem services (ES, e.g. timber production, biodiversity, recreation) in the face of uncertainties about the degree of future climate change (e.g. Yousefpour et al. 2017). Maintaining the multitude of ES under climate change is particularly important for mountain forests, which provide important ES for the mountain regions themselves [e.g. protection functions against gravitational hazards, Elkin et al. (2013), Irauschek et al. (2017a)] as well as downstream (EEA 2010; Langner et al. 2017).

Climate change impacts on mountain forests can be highly heterogeneous in space, i.e. varying in particular with elevation and local topography (Lindner et al. 2010). While low-elevation valley bottoms are likely to become

Communicated by Rüdiger Grote.

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s10342-020-01263-x) contains supplementary material, which is available to authorized users.

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increasingly prone to drought-induced forest die-off (e.g. Bigler et al. 2006; Jump et al. 2006), higher elevations on the contrary tend to benefit from longer vegetation periods and thus better growing conditions (Lindner et al. 2010; Bugmann et al. 2014). However, high spatial heterogeneity (e.g. in terms of topography) and local site and stand conditions (e.g. soil conditions, species composition) can superimpose these larger-scale trends (Lindner et al. 2010) and potentially lead to complex, site-specific forest responses to climate change (e.g. Etzold et al. 2019). Previous studies providing climate change impact assessments for mountain forest managers therefore emphasized the importance of local site and stand conditions at a relatively fine scale and high resolution (Irauschek et al. 2017a; Klopcic et al. 2017; Mina et al. 2017b).

The rising awareness of the importance of mountain forests and their multiple ES has induced an increasing research interest in the past years (Lexer and Bugmann 2017). Due the expected extent of environmental changes (e.g. SCNAT 2016) and the long planning horizons in mountain forests, dynamic vegetation models (DVMs) have become a central tool for assessments of climate change impacts (e.g. Seidl et al. 2011a). Besides their suitability to climate change applications, a further advantage of most DVMs is their ability to consider a wide range of species (Pretzsch et al. 2008) and explore the benefits of species mixtures (Forrester et al. 2017). Furthermore, various DVMs have been expanded over the last years to represent a diverse array of management techniques (e.g. Rasche et al. 2011; Lafond et al. 2014; Irauschek et al. 2017b). Altogether, these developments have substantially improved the suitability of DVMs to assess the effect of management and climate change on future forest development and ecosystem service provisioning in a mountain context (e.g. Maroschek et al. 2015; Mina et al. 2017a).

In spite of the availability of assessments at larger (e.g. national) scales (e.g. Lexer et al. 2002; Bircher et al. 2015), still only few studies are available for mountain forests at the local scale, providing decision support at the level required by an individual forest enterprise (see, for example, Maroschek et al. 2015). Furthermore, findings from one case study area may apply only to a limited degree to another area, particularly if environmental conditions are markedly different (see, for example, Elkin et al. 2013). Mountain forest managers thus face the challenge to estimate how studies from other regions or assessments at larger scales apply to their specific enterprise, and they may therefore benefit significantly from DVM assessments that account for the specific local conditions within their forest enterprise.

Initiated and co-developed by the local forest manager, we provide and evaluate the utility of a DVM application for decision support in a large forest enterprise in the Northern Pre-Alps (the Oberallmeindkorporation Schwyz, OAK-SZ) in Switzerland. The study area covers a large environmental gradient from drought-affected sub-montane to currently temperature-limited sub-alpine stands. As in many other mountain regions of Europe, a primary goal of forest management in the OAK-SZ is to maintain their protection function against gravitational hazards, in particular against rockfall and avalanches (see also Bebi et al. 2016). While some stands may benefit from a warming under a moderate climate change scenario, a higher frequency and intensity of extreme drought events may reverse this trend and cause abrupt changes up to the point of complete forest dieback (Allen et al. 2015), with potentially fatal consequences for the forests' protection function (Elkin et al. 2013; Bebi et al. 2016). An aspect of particular importance for forest management is therefore whether stands are more likely to change in a gradual or abrupt way, and at which time horizons these changes are to be expected (Temperli et al. 2012). Besides the direct effects of altered temperature and precipitation, further climate-related processes are likely to impact future forest development, most notably overstorey disturbances [e.g. bark beetle outbreaks, Temperli et al. (2013), Seidl et al. (2017)] as well as intensified browsing pressure due to high ungulate populations (Côté et al. 2004; Schulze et al. 2014).

The purpose of this study is therefore to address a set of stakeholder-defined management questions at a high local resolution within the forest enterprise, which thus complements larger-scale assessments (Bircher et al. 2015) and results from local-scale studies from other mountain areas (e.g. Irauschek et al. 2017a; Mina et al. 2017a). Due to its particular location in an area of steep environmental gradients from water-limited to temperature-limited forests, the study furthermore provides an informative case for other managed mountain forests in the Northern Alps, where contrasting climate change impacts can be expected to occur along elevational gradients (cf. Lexer and Bugmann 2017).

Using the DVM ForClim (Bugmann 1996; Huber 2019), which has been developed for climate change applications in mountain forests of the Central European Alps, we addressed the following research questions, which were defined as the basis for long-term planning and future decision-making by the local forest manager:

(1) *Where* are the largest changes to be expected in terms of basal area and species composition for two contrasting climate change scenarios ('low' and 'high impact')?
(2) *When* are changes in structure and composition to be expected? Are these changes gradual or abrupt?
(3) *Which* effect will large-scale disturbances (windthrow, bark beetles) have at spruce-dominated sites under a 'high-impact' climate scenario? How is post-disturbance recovery affected by previous forest management and the level of ungulate browsing?

Methods

Forest model ForClim

ForClim is a climate-sensitive dynamic vegetation model developed for short- and long-term simulation of forest dynamics (Bugmann 1996). It belongs to the group of 'forest gap models', which simulate forest properties emerging from individual-level interactions under the influence of site-specific environmental conditions (e.g. temperature, precipitation, topography, soil conditions, etc.). A forest is represented by multiple small patches, with the patch size equivalent to the area dominated by a single large tree individual (Botkin et al. 1972) based on the concept of patch dynamics (Watt 1947). Within each patch, tree demography is simulated explicitly at annual time steps in the form of establishment, growth and mortality of tree cohorts (i.e. groups of trees of the same species and age, Bugmann 1996). Environmental effects on tree growth are represented via growth-reduction factors, i.e. environmental conditions that deviate from the optimum reduce species-specific growth (see also Bugmann 2001).

ForClim has been applied across various temperate forests in Europe and other parts of the world (e.g. Gutierrez et al. 2016; Mina et al. 2017a, b; Huber et al. 2018) and undergone thorough evaluation under a wide range of species and site conditions (Rasche et al. 2012; Huber 2019). Over the past decade, the capacities of ForClim to represent forest management have been continuously expanded and evaluated in several mountain regions across Europe (Rasche et al. 2011; Mina et al. 2017a). All simulations of this study were conducted with ForClim Version 4.0.1 (Huber 2019); see Online Resource 1 for further details.

Study areas

Within the planning unit of the 'Oberallmeindkorporation Schwyz' (subsequently abbreviated as OAK-SZ), five sites were selected (Fig. 1) to represent (1) the most frequent forest communities (Ellenberg and Klötzli 1972) per elevation zone (see Table 1) which were characteristic for the forest enterprise and (2) stands in the timber stage of development (i.e. dominant DBH > 30 cm), which had highest priority from a forest management perspective. The study region is located in the Northern Alps and features a pronounced precipitation gradient over a relatively short distance, ranging from moderate annual precipitation amounts of ca. 1100 mm at the south-eastern part of Lake Lucerne to > 2000 mm in the valleys in its east and north-east (HADES 2015). Furthermore, soil conditions differ considerably among the sites due to distinct differences in climate, geology, vegetation and topography (particularly slope angle). While the study sites Brünischart (BS) and Fronwald (FW) are characterized by relatively low soil water holding capacity (SWHC) due to steep slopes and shallow soil depth on calcareous bedrock (Hantke and Kuriger 2003), deeper soils with a higher SWHC occur at higher elevations, i.e. the study site of Herrenwald (HW), Tröliger Wald (TW) and Schwarz Stock (SSt, see Table 1). In terms of species composition, the lowest elevation site BS is characterized by a broadleaf-dominated forest, while the higher-elevation sites are dominated by coniferous species (particularly *Abies alba* and *Picea abies*, see Table 1 for details). The stand structure of each site was measured within 1 ha plots during July to September 2018, with the exception of FW (Riemenstalden site 01-053.001, Schwitter 2006), where data were provided by the Experimental Forest Management project under the lead of David I. Forrester (Forrester et al. 2019). Details about the stand initialisation are provided in Online Resource 1.

Small-scale 'mountain forest plentering' silviculture

Forest management in mountain regions is particularly difficult, since management options become increasingly constrained towards higher elevations and promoting sufficient regeneration is a considerable challenge (Schwitter 2013). The management technique of 'mountain forest plentering' (MFP) silviculture has been developed to cope with the specific situation in mountain forests, in particular to induce regeneration (Schwitter 2013; Leuch et al. 2017). MFP represents a small-scale removal of collectives of trees (rather than individual trees as done in lowland plenter forests, Schwitter 2013) with the objective to foster regeneration via improved light and temperature conditions at the forest floor (Leuch et al. 2017).

A new MFP management module was therefore designed for ForClim to harvest tree collectives in small patches of 400 m^2 (i.e. the ForClim patch size in this study) within the forest. Although not being spatially explicit, this routine mimics the approach underlying cable yarding, where the goal is to remove a pre-defined fraction of the standing volume per stand. The harvest intensity is therefore defined as the target timber volume (Vol_{Target}), representing the fraction of volume within the entire stand (i.e. all patches) to be harvested per intervention. Besides, a species-specific target diameter (DBH_{Target}) has to be defined by the user, representing the diameter threshold above which trees can be harvested. Furthermore, the time interval between the management interventions has to be defined by the user. The MFP module assures that scheduled harvest interventions are only carried out if sufficient harvestable volume (i.e. the prescribed Vol_{Target}) is available in the entire stand (i.e.

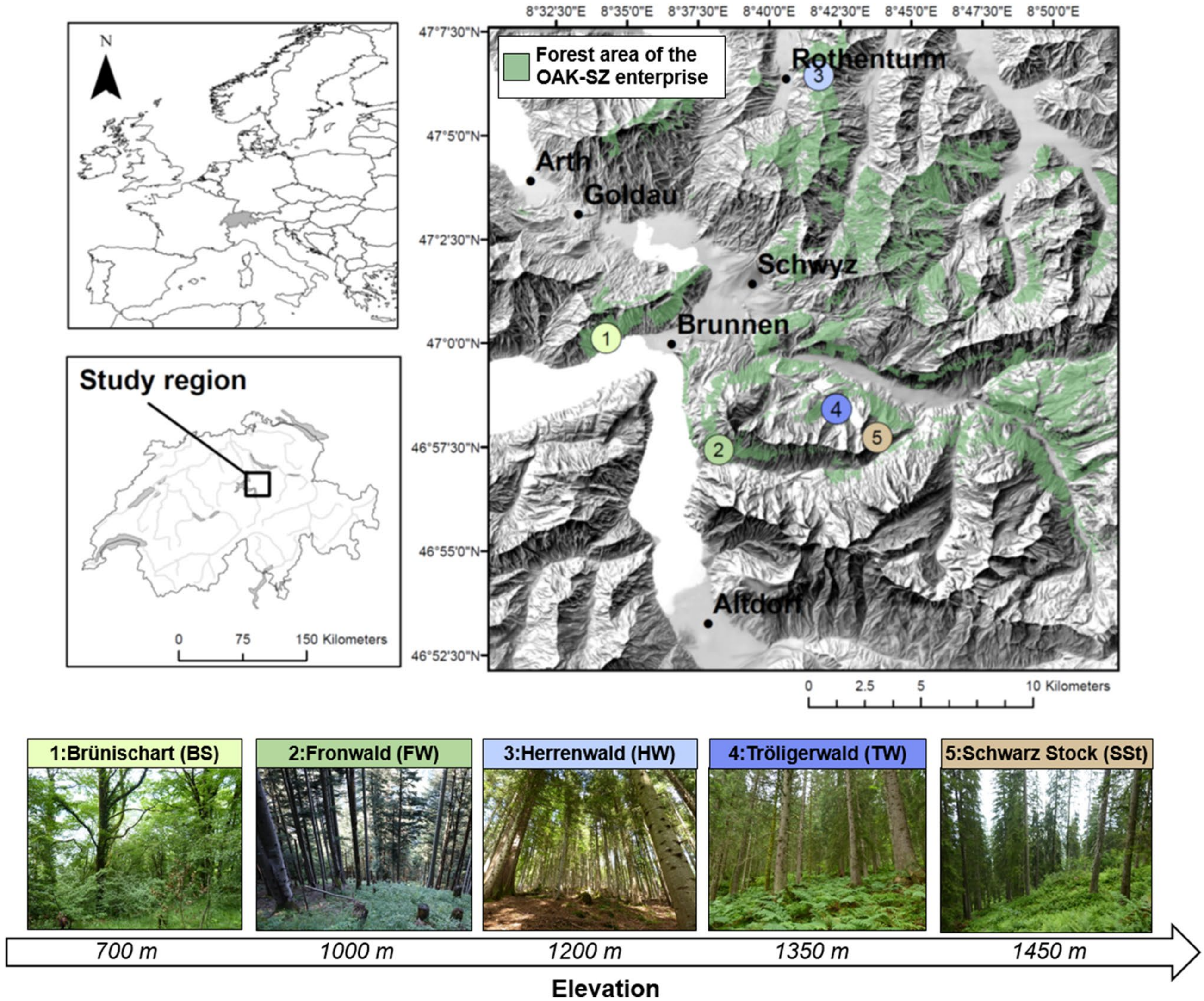

Fig. 1 Location of study sites within the management area of the forest enterprise 'Oberallmeindkorporation Schwyz' (OAK-SZ), Switzerland. Hillshade map © Swisstopo

all patches) to mimic the situation that expensive mountain forest harvest interventions are only conducted if the intervention is cost-effective, i.e. sufficient timber can be harvested. If sufficient harvestable timer is available for the intervention, the module progressively harvests all trees within randomly chosen patches above the user-defined DBH_{Target}, thus creating gaps with favourable light conditions for regeneration while not removing the regeneration that is present already (if any, so-called advance regeneration). Notably, the module assures that the same patch is only harvested once per rotation cycle, i.e. a patch is not harvested in two consecutive interventions as long as other unharvested patches are available. Further details about the MFP module can be found in Online Resource 1.

All MFP management interventions were scheduled at 20-year intervals for all sites, starting from 2019. The management prescriptions differed between the lower-elevation sites (BS and FW) and the higher-elevation sites (HW, TW and SSt) accounting for the different conditions along the elevation gradient. For the lower-elevation sites, all interventions were carried out with the same management intensity (Vol_{Target} of 15%) for all harvest interventions, applying a DBH_{Target} of 40 cm for Picea abies and 60 cm for all other species. For the higher-elevation sites, a higher intensity intervention was carried out in the first harvest year 2019 (Vol_{Target} of 25%), followed by lower intensity harvests (Vol_{Target} of 15%) in the subsequent interventions. At the high elevations, a DBH_{Target} of 12 cm was defined for all species.

Table 1 Elevation zones (following the definition of Frehner et al. 2005), environmental conditions (MAT: mean annual temperature; AP: annual precipitation sum), dominant tree species and respective forest community (Ellenberg and Klötzli 1972) for the study sites (as described in ATRAGENE 1997, 1999, 2004). Species abbreviations: QuPetr: *Quercus petraea*, PiSylv: *Pinus sylvestris*, AcPseu: *Acer pseudoplatanus*, AbAlba: *Abies alba*, PiAbie: *Picea abies*

Site	Elevation (m. a.s.l.)	Elev. zone	MAT (°C)	AP (mm)	Slope (°)	Aspect	Soil type	Soil depth (cm)	Dom. tree species	Forest community (Ellenberg and Klötzli 1972)
Brünischart (BS)	700	Sub-montane	8.63	1178	> 30	SE	Rendzina	40–60	*QuPetr, PiSylv, AcPseu*	40C
Fronwald (FW)	1000	Lower montane	6.11	1360	> 30	SW	Rendzina	50–60	*AbAlba, PiAbie*	12
Herrenwald (HW)	1200	Upper montane	5.02	2000	10–30	S	Brown soil	100	*PiAbie, AbAlba*	19
Tröliger Wald (TW)	1350	High montane	4.67	2010	10–30	N	Brown soil	80	*PiAbie*	46D
Schwarz Stock (SSt)	1450	Sub-alpine	4.42	2033	> 30	N	Podzol	70	*PiAbie*	57S

Calculation of ecosystem services

Changes in aboveground biomass, species composition and forest structure were measured in terms of basal area (m^2 ha^{-1}), and protection against gravitational hazards was calculated as dimensionless protection indices, i.e. avalanche protection index (API) and rockfall protection index (RFPI), developed by Elkin et al. (2013) and Schmid (2014) based on Frehner et al. (2005). The API contains an interception component (calculated from stand leaf area index, LAI, and the relative share of coniferous trees in the stand) and a stability component associated with stem density (based on the number of trees with a DBH > 8 cm). The resulting index varies between 0 and 100, with an API of 100 representing maximum protection. The RFPI is based on stem density and diameter distribution, which determines the capacity of the stand to protect against rocks of certain sizes. For the present study, a collective index was calculated for all rock size classes, as described in Schmid (2014). As for the avalanche protection index, the RFPI index varies between 0 (no protection) and 100 (max. protection function). Further details and formulae are given in Online Resource 1.

Simulation scenarios

Simulations of future forest dynamics were conducted for present climate and two contrasting climate change scenarios that represented a 'low-impact' scenario (RCP3PD, compliant to the targets of the Paris Agreement) and a 'high-impact' scenario (A2, i.e. unabated emissions), based on the CH2011 report for Switzerland (CH2011). For present climate conditions, the time series from 1931 to 2017 from the WSL database of spatially interpolated climate data derived using DAYMET (Thornton et al. 1997) was applied (cf. Online Resource 1). The 'low-impact' scenario features a moderate increase in annual mean temperature by + 1.5 °C and decrease in annual precipitation sum by − 10% until the end of the twenty-first century (relative to the baseline period of 1980–2011), while the 'high-impact' scenario represents a temperature increase by + 4 °C and precipitation decrease of − 25% (CH2011). Further details about the climate change scenarios are provided in Online Resource 1.

Furthermore, two contrasting scenarios for ungulate browsing pressure ('low browsing' and 'high browsing') were considered in the simulation setup, since browsing damage to tree regeneration is a considerable problem in many mountain forests (Kupferschmid et al. 2015). Browsing in ForClim affects the density and species composition of tree regeneration, depending on browsing pressure and a species-specific browsing tolerance (Didion et al. 2011, see also Online Resource 1, section 'Browsing scenarios' for details).

To assess the importance of management on forest dynamics under climate change, two scenarios were compared: one without any management interventions and one including the MFP management (cf. above and Online Resource 1 for details). All simulations were run for 150 years, as in Mina et al. (2017b). Since close-to-nature forestry is an important management guideline in many parts of Europe (Bauhus et al. 2013), simulations determining the potential natural vegetation (PNV) at each site were conducted to provide additional information on this 'natural reference state' for forest management. These simulations were run for 1000 years under all climate scenarios, in the absence of management, and under a low browsing pressure.

In addition to the direct effects of temperature and precipitation changes, climate change is also likely to lead to intensified disturbance regimes (Seidl et al. 2017). Since predicting the exact timing of disturbance occurrence is practically impossible (Mina et al. 2017b), we investigated forest dynamics following a set of exemplary large-scale disturbances by windthrow and bark beetle outbreaks, two key disturbance types in Central European forests (Seidl et al. 2011b). These simulations were carried out for the site TW (1350 m), a typical mature, spruce-dominated stand that is structurally prone to both windthrow and bark beetle disturbances. To evaluate the effects of the timing of disturbance occurrence under a strong warming scenario, exemplary disturbance scenarios were simulated under the 'high-impact' climate change scenario for the years 2030 and 2070 with and without pre-disturbance management (cf. Online Resource 1 for detailed information).

All results refer to forest structure and composition at the end of the simulation period (year 2150), unless stated otherwise. The simulations were carried out with ForClim version 4.0.1 (Huber 2019), and all analyses and visualisations were carried out with R Version 3.4.3 (R Development Core Team 2017).

Results

Elevation-specific magnitude of changes in structure and composition

For the 'low-impact' climate scenario, only small changes in basal area, but noticeable shifts in species composition occurred across the five sites until 2150 (Fig. 2). Species shifts were most pronounced at the sites ≤ 1000 m a.s.l. (i.e. BS and FW), where warmth-adapted broadleaved species (particularly *Fagus sylvatica* and *Tilia cordata*) increased in abundance. Higher-elevation sites experienced an increase

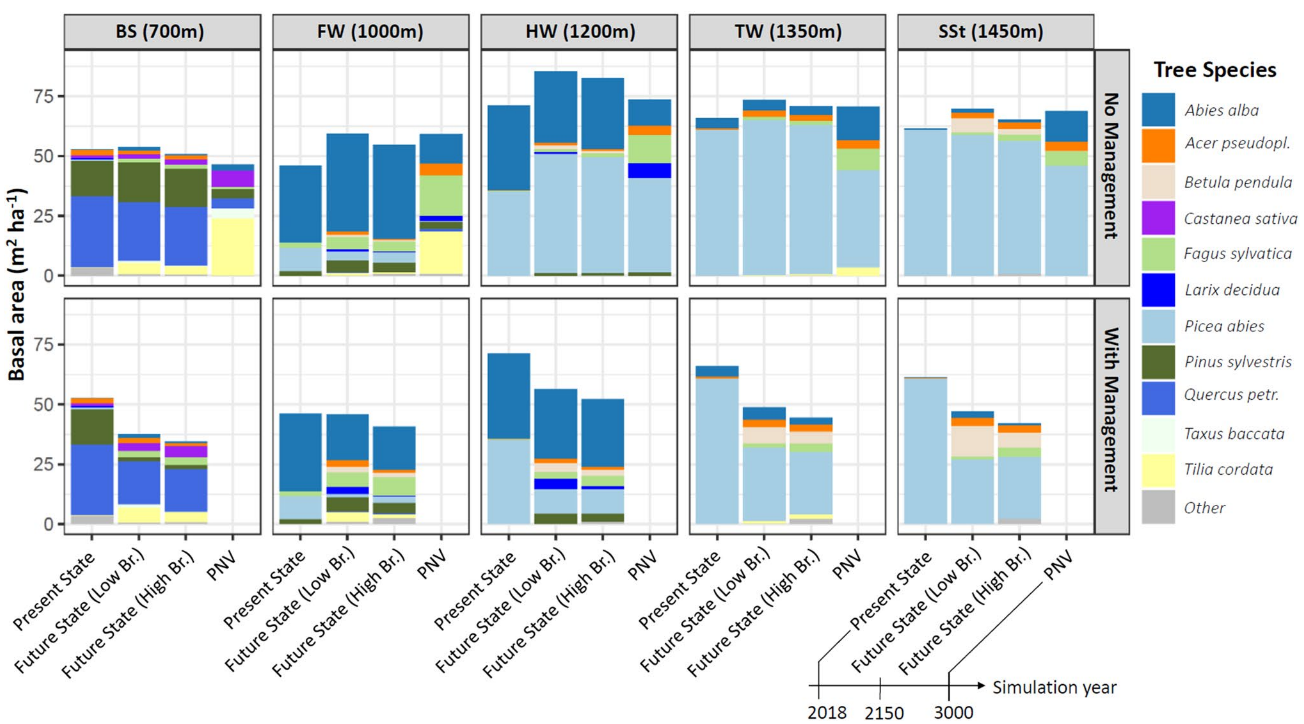

Fig. 2 Stand basal area under the 'Low-impact' climate scenario (RCP3PD) at the five study sites for unmanaged (top row) and managed (bottom row) conditions. 'Present state' refers to measured initial state at year 2018, 'Future state' (with 'low' and 'high' browsing pressure) refers to stand state at simulation year 2150, and 'PNV' refers to potential natural vegetation establishing after a simulation time of 1000 years under novel climatic conditions (only for unmanaged conditions)

in *Fagus sylvatica*, partly at the expense of *Picea abies* (e.g. site SSt). The PNV simulations for BS and FW (Fig. 2, top row) showed that these trends indicate a long-term shift in species dominance.

Simulations including forest management (Fig. 2, bottom row) showed a higher share of early successional species (e.g. *Betula pendula*) as well as a shift towards more thermophilic broadleaved species in the regeneration layer (e.g. *Fagus* and *Acer*, Online Resource 3, Fig. A3.14ff.), representing an earlier transition towards a species composition in equilibrium with climate (see PNV results). However, this transition in the regeneration layer was inhibited by high browsing pressure (Fig. 2, 'high browsing pressure'; cf. Online Resource 3), which reduced basal area and substantially reduced regeneration density (Online Resource A3, e.g. Fig. A3.15).

For the 'high-impact' climate scenario, drastic reductions in basal area occurred for the lower-elevation sites BS and FW, while the other sites located at higher elevations increased in basal area until the year 2150 (Fig. 3, top row). For BS, the previously broadleaf-dominated stand experienced a complete transition to a *Pinus sylvestris*-dominated woodland, which featured low basal area (< 15 m^2 ha^{-1}) and was characterized by low densities of large trees (> 30 cm DBH), particularly under 'high browsing' conditions (Online Resource 3, Fig. A3.3 and Fig. A3.5). In terms of species composition, all other sites showed increasing shares of broadleaved trees (particularly *Tilia* for the site FW and *Fagus* at the other sites). Simulations including forest management showed higher shares of these species in the regeneration layer (Fig. 3 and Online Resource 3, Fig. A3.9ff.) and, by the year 2150, were closer to the PNV composition (Fig. 3).

These climate-induced changes affected the basal area and protection function of all sites, although the magnitudes of change differed between the two climate scenarios (Fig. 4, Online Resource 2, Fig. A2.4–2.6). For the 'low-impact' climate scenario, only slight decreases in basal area resulted for the low-elevation sites (BS and FW), and higher basal area as well as rockfall and avalanche protection for the high-elevation sites (Fig. 4). These patterns were much more pronounced for the 'high-impact' scenario, where basal area and protection functions decreased dramatically for the low-elevation sites. At the high-elevation sites, basal area as well as rockfall and avalanche protection increased. In general, similar patterns emerged under either browsing scenarios, although the magnitude of changes was higher in the 'high browsing pressure' scenario, particularly for avalanche protection (Fig. 4 and Online Resource 2, Fig. A2.4–2.6).

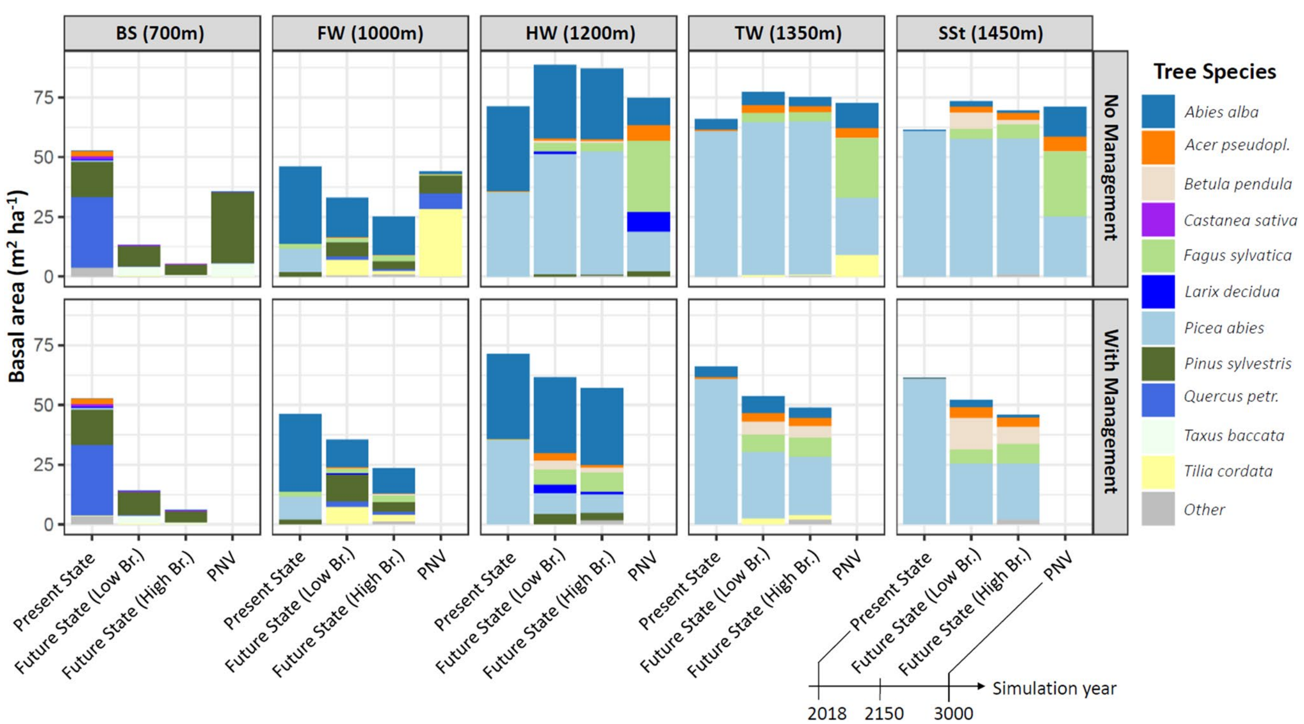

Fig. 3 Stand basal area under the 'High-impact' climate scenario (A2) at the five study sites for unmanaged (top row) and managed (bottom row) conditions. 'Present state' refers to measured initial state at year 2018, 'Future state' (with 'low' and 'high' browsing pressure) refers to stand state at simulation year 2150, and 'PNV' refers to potential natural vegetation establishing after a simulation time of 1000 years under novel climatic conditions (only for unmanaged conditions)

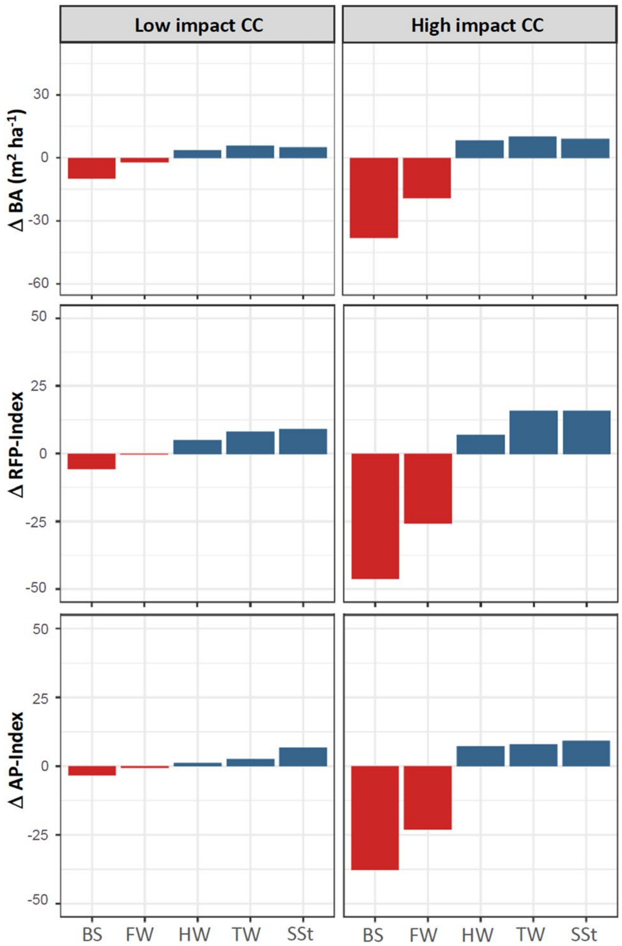

Fig. 4 Changes in basal area, rockfall protection (RFP) and avalanche protection (AP) index for all sites at year 2150 under the 'low-impact' (RCP3PD) and 'high-impact' (A2) scenario relative to present climate. Colours indicate the direction of change (red: decrease, blue: increase). Note that results shown here refer to the 'with management' and 'high browsing' simulations. Results for the 'no management' and 'low browsing' simulations feature similar patterns and are provided in Online Resource 2

Temporal patterns of change

Temporal patterns of change in basal area differed substantially between the five sites and among the two climate change scenarios and were consistent for unmanaged (Fig. 5) and managed stands (Online Resource 3, Fig. A3.4ff.). While the 'low-impact' climate scenario showed only gradual changes until the year 2150, abrupt changes occurred under the 'high-impact' climate scenario for the low-elevation sites BS and FW. Furthermore, the onset of a decreasing trend for BS and FW differed between the climate scenarios: for the 'low-impact' scenario, basal area remained nearly constant until 2080, whereas it started to decrease already around 2050 for the 'high-impact' scenario (Fig. 5). Moreover, abrupt changes in basal area under the 'high-impact' scenario occurred at different time points depending on the site. While BS experienced an abrupt dieback already by 2060–2080, the site FW experienced a strong drought-related decrease only towards the end of the twenty-first century, and to a smaller extent (Fig. 5 and Online Resource 2, Table A2.1, Fig. A2.9).

Disturbance effects

Both exemplary disturbance simulations for windthrow and bark beetle at the spruce-dominated site TW (1350 m) under a 'high-impact' climate scenario had a similarly drastic effect, reducing stand basal area to < 10 m^2 per ha (Fig. 6 and Online Resource 3, Fig. A3.26ff.). The reduction in stand basal area was higher when the disturbances occurred earlier (i.e. in 2030 compared to 2080), which was due to a lower abundance of advance regeneration prior to year 2030 (Online Resource 3, Fig. A3.26 and Fig. A3.30). Furthermore, tree regeneration and growth benefited more from the warmer conditions prevailing in 2080 compared to 2030, leading to a faster recovery of basal area (Fig. 6). The recovery was, however, substantially impeded by high browsing pressure (Fig. 6).

Regarding the effect of pre-disturbance forest management, basal area was up to 30% higher at the end of the first decade after disturbance if the stand had previously been managed by mountain forest plentering than if no management had been conducted (Fig. 7 and Online Resource 2, Fig. A2.7). This was due to a higher abundance of advance regeneration in the managed stands, which contributed substantially to post-disturbance recovery (Online Resource A3, cf. Fig. A3.26 and Fig. A3.28). The legacy effect of previous management decreased with time since disturbance, but high browsing pressure continued to shape the trajectory of long-term recovery (Fig. 6 and Online Resource 2, Fig. A2.8).

Discussion

Our results showed contrasting responses to climate change along the elevational gradient within the forest enterprise, with negative impacts likely to occur at the lower-elevation sites (≤ 1000 m a.s.l.), whereas higher-elevation sites are more likely to benefit from warmer conditions in the absence of disturbances. In contrast to the 'low-impact' climate scenario, abrupt negative impacts occurred for low-elevation sites under the 'high-impact' scenario from the mid-twenty-first century onwards, leading to substantial shifts in species composition and stand structure as well as a severe loss of protection function. Following our research questions, we first discuss (1) the elevation-specific magnitude of change and (2) their temporal dynamics, including the response to

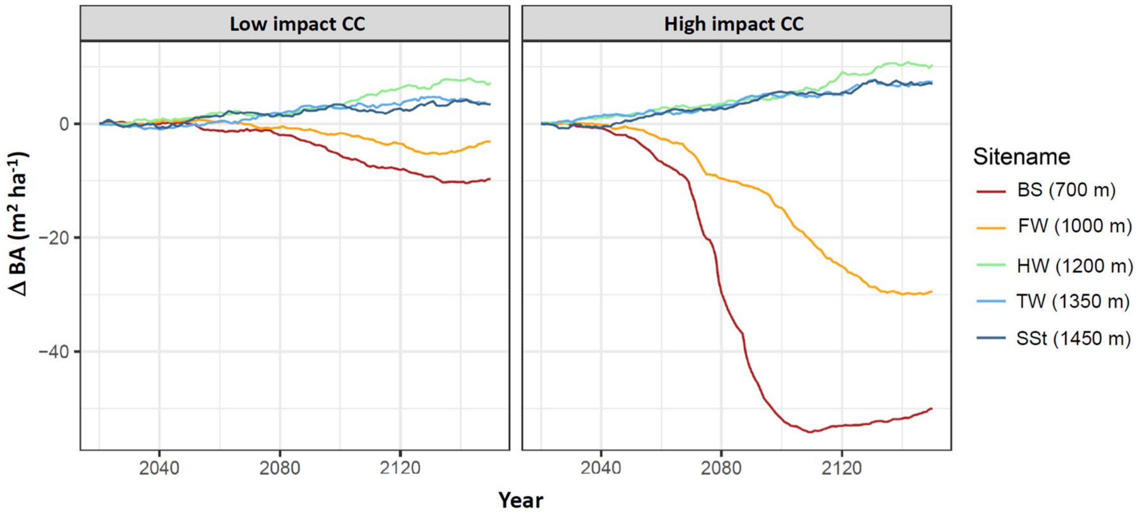

Fig. 5 Development of basal area over time under the 'low-impact' (RCP3PD) and 'high-impact' (A2) scenario, shown as the difference to the respective trajectory under present climatic conditions for the five study sites under unmanaged conditions

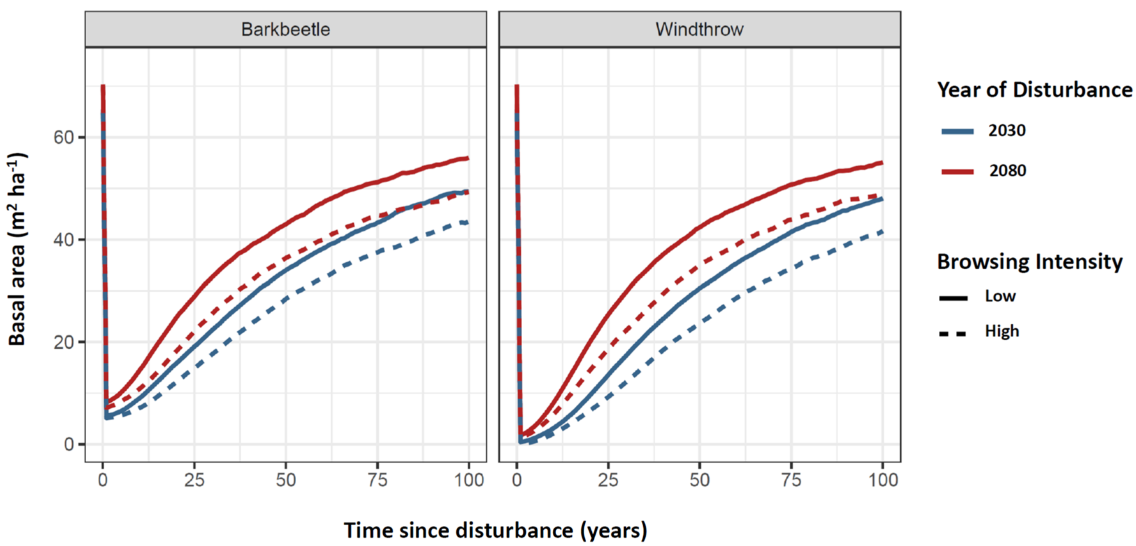

Fig. 6 Post-disturbance recovery of basal area for the exemplary bark beetle and windthrow disturbance scenarios at the site TW (1350 m). Different colours indicate the different time point of disturbance occurrence (2030 or 2080). Different line types indicate the browsing intensity. Simulations assumed a 'high-impact' (A2) climate change scenario without pre-disturbance management

the exemplary disturbance scenarios. Ultimately, we discuss (3) the limitations of this study and further capabilities of DVMs to provide decision support for forest managers.

Elevation-specific magnitude of change

Elevation and topography are key factors altering the local climate in mountain landscapes due to, for example, the temperature gradient with elevation, orographic rainfall and varying incident solar irradiation with aspect and slope (Whiteman 2000; Zou et al. 2007). The five stands of our study were located across a gradient from drought-prone, steep south-facing sites at lower-elevation to moist, north-facing sites at high elevation. These contrasting conditions were reflected in the differential climate change impacts, with detrimental effects predominating at the two low-elevation sites with southerly aspect (BS and FW). Empirical studies from dry inner-alpine valleys in Central Europe show similar patterns under contemporary climate change, i.e. significantly higher drought-induced mortality at elevations < 1000 m (Minerbi et al. 2006; Rigling et al. 2013) and decreased regeneration densities on low-elevation south-facing slopes

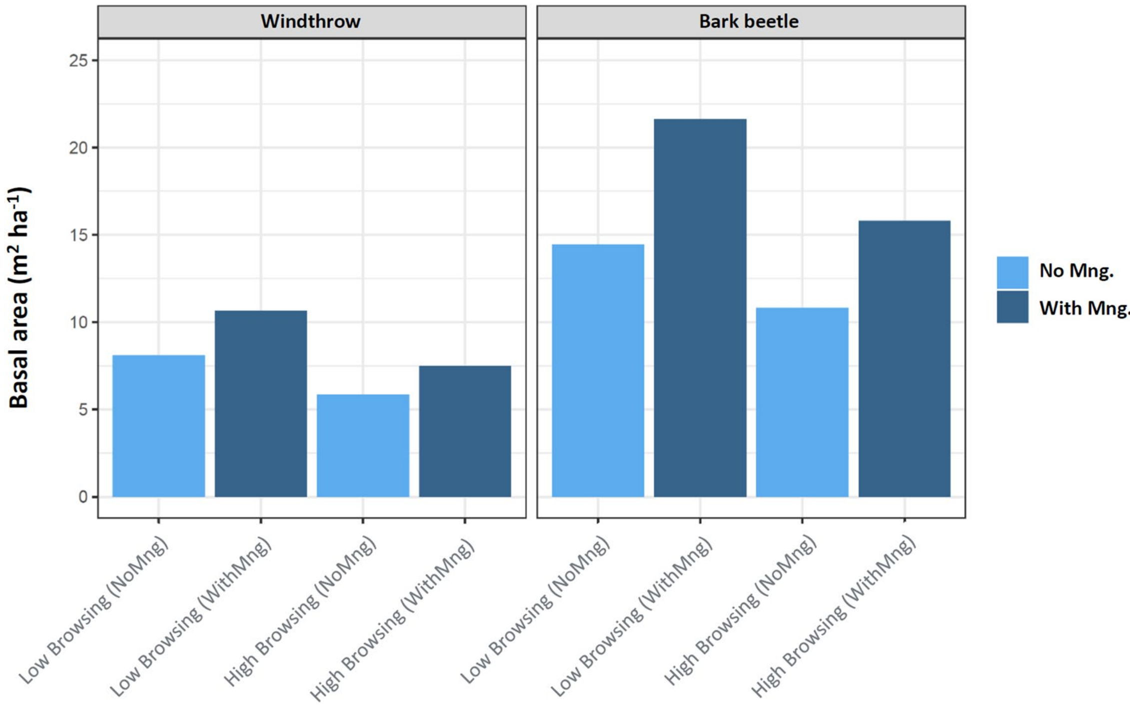

Fig. 7 Basal area at the end of the first decade after disturbance in 2080 for the two exemplary disturbance scenarios (windthrow and bark beetle) under low and high browsing, as well as managed (‘WithMng’) and unmanaged (‘NoMng’) conditions at the site TW (1350 m). Results for the disturbance in year 2030 are shown in Fig. A2.5 (Online Resource A2)

(e.g. Wohlgemuth and Moser 2018). However, the comparison of the simulated climate change impacts for the site BS with the results from dry inner-alpine valleys is restricted by the distinctly different climatic conditions between the respective regions (e.g. Elkin et al. 2013). At the site BS, high precipitation amounts during summer prevent severe droughts under present climate conditions (see Online Resource 2, Fig.A2.9) and permit the growth of a mixed deciduous forest with relatively high basal area in spite of the low soil water holding capacity (ATRAGENE 1997). Nevertheless, our simulation results indicate that a number of severe droughts under future climate change may change the situation rapidly and emphasize the particular vulnerability of the low-elevation, south-facing site BS among the gradient of simulated sites within the forest enterprise.

This site-specific response exemplifies the challenge that mountain forest managers are facing and shows how DVMs can provide decision support for forest planning with a local resolution. On the one hand, large-scale assessments provide important information on climate change impacts (e.g. Bugmann et al. 2014; Bircher et al. 2015; SCNAT 2016), which may, however, not be at a sufficiently detailed level for mountain forest enterprises located in topographically complex and environmentally contrasting settings. As shown by the recent empirical study by Etzold et al. (2019), patterns of climate-induced forest mortality in Switzerland are highly complex and depend on the combination of species effects and small-scale site conditions. An evaluation based on species composition alone may, for instance, conclude that the stand BS (dominated by drought-tolerant oak and pine) would be more resistant to drought impacts than FW (dominated by the less drought-tolerant *Abies alba* and *Picea abies*, e.g. Leuschner and Meier 2018). While the ‘low-impact’ climate scenario indeed caused little change in forest structure and composition at BS, the ‘high-impact’ climate scenario induced drastic diebacks at this site, despite the predominance of drought-tolerant species. In contrast, the higher-elevation site FW was less impacted despite the predominance of more drought-sensitive conifers. Our study thus supports the findings of context-specific climate change impacts, which depend strongly on the specific abiotic and biotic conditions (Condes and del Rio 2015; Sanchez-Salguero et al. 2015; Etzold et al. 2019).

The simulated ‘high-impact’ climate change effects at low elevations have pronounced consequences for the services provided by the respective stands, since the decrease in basal area implies a loss of harvestable timber as well as a severe loss of protection function against gravitational hazards. In the absence of a continuous forest cover, avalanche release risk is substantially higher since the forest cover decreases snowpack depth (due to higher snow interception), alters microclimatic conditions and increases surface roughness

(Frehner et al. 2005). Similarly, rockfall risk increases drastically as stands formerly characterized by a large range of size and densities lose their well-structured characteristics (Dorren et al. 2005). According to Bebi et al. (2016), the importance of rockfall (as well as landslides and erosion) is expected to increase more than the importance of avalanches under climate change. Although the seasonal time window with critical snowcover for avalanches is likely to decrease with climate change, avalanche risks at lower elevations should not be underestimated, particularly regarding snow-gliding on steep south-facing slopes (Bebi et al. 2016), e.g. at the site BS. In the case of rockfall, an adaption towards a coppice management could, however, diminish this increasing risk and improve the protective function of the lower-elevation, broadleaf-dominated forests (e.g. Radtke et al. 2014).

An additional level of decision support that can be provided by a DVM-based approach is the local-scale composition of potential natural vegetation (PNV), which represents the emerging species compositions under novel climate conditions. Although the drastic dieback at the site BS was projected to lead to very low basal areas for the end of the twenty-first century, the PNV simulations imply that a *Pinus sylvestris* forest would re-establish in the long term even under a 'high-impact' climate scenario. It is, however, possible that besides *Pinus sylvestris*, more drought-tolerant sub-Mediterranean tree species could immigrate at the low-elevation BS site in the future, such as pubescent oak (*Quercus pubescens*), which is becoming an increasingly important tree species in dry central Alpine valleys (Rigling et al. 2013). As recently demonstrated by Huber (2019), the immigration of more climate-adapted species could play an important role in buffering negative impacts of climate change. Altogether, the combination of insights from empirical studies (e.g. Frank et al. 2017, Wohlgemuth et al. 2018) as well as from DVM-based assessments can thus provide important decision support regarding which tree species to favour at a specific location in the long term.

In contrast to the detrimental impacts at low elevations, the 'high-impact' climate scenario led to increases in basal area and a shift in species composition towards more thermophilic broadleaved species at the high-elevation sites (> 1000 m a.s.l.). Although the increase in basal area suggests a positive development for forest management (i.e. provisioning of more harvestable timber), simulated species composition showed a strong discrepancy compared to the PNV simulations by the year 2150, indicating that the high fraction of Norway spruce (*Picea abies*) remaining in the simulated stands is unlikely to represent a climatically suitable forest composition (cf. Bugmann et al. 2014). Particularly under unmanaged conditions, stand structure in the year 2150 was characterized by a high number of tall, old spruce trees, indicating a high susceptibility to windthrow (Seidl et al. 2014; Schuler et al. 2019). Furthermore, climate change likely leads to an increase in the risk of bark beetle outbreaks at higher elevations due to an increase in the number of generations per year and prolonged annual flight periods (Temperli et al. 2013; Bugmann et al. 2014). The advantages of increased growth may thus be counteracted by negative impacts of enhanced biotic or abiotic disturbances, as shown in our exemplary disturbance simulations. Including forest management in our simulations, however, induced the regeneration of more climate-adapted species (particularly *Fagus* and *Acer*) and led to a faster transition towards a less vulnerable mixed species forest at higher elevations.

With respect to species responses to climate change along the elevation gradient, our simulation results showed an upslope spread of thermophilic, broadleaved species, particularly under the 'high-impact' climate scenario. This is in line with an increasing number of observations under contemporary climate change that are reporting an upward expansion of the distribution ranges of trees (e.g. Penuelas and Boada 2003; Vitasse et al. 2012), although species-specific responses can be complex and site specific (e.g. Gazda et al. 2019). Furthermore, palaeoecological studies show similar upward shifts of broadleaved species during periods with higher temperatures, e.g. for *Tilia* during the Holocene temperature maximum (Thöle et al. 2016), and suggest an increase in the abundance of *Fagus sylvatica* at high elevations under future climate change (Schwörer et al. 2014). The projected shifts of dominant species are thus in general agreement with patterns found in empirical studies of past and contemporary climate change, although the responses of some subdominant species (e.g. increase in *Betula pendula* at high-elevation managed sites) may be overestimated (cf., e.g. Wohlgemuth and Moser 2018).

Temporal patterns of change

Estimating the most likely pathway of future climate change is difficult due to uncertainties in the future of socio-economic and technological developments (IPCC 2013). While trajectories of temperature changes show relatively small differences between the emission scenarios in the first half of the twenty-first century, they differ substantially until the end of the century for Switzerland (CH2011). A similar trend was evident from the simulated forest properties, with little change until around 2040, but substantial differences between the climate change scenarios thereafter. The rates of change are of particular importance in this context (cf., Reyer et al. 2015), tending to be gradual for the 'low-impact' scenario, but more abrupt for the 'high-impact' scenario at sites ≤ 1000 m a.s.l. While the specific time points of these drastic changes are subject to considerable uncertainty, several studies suggest a much higher probability and frequency of drought events in the twenty-first century (e.g. Dai 2013). The combination of higher temperatures and lower precipitation is likely to lead to tipping point dynamics, resulting in sudden drought-related tree mortality (Allen et al. 2015). The risk of this sudden dieback is particularly high for tree species currently growing under unsuitable climatic conditions, as shown, e.g. for *Picea abies* at low elevations (e.g. Levesque et al. 2013). In accordance with these findings, our results suggest that a 'high-impact' climate change scenario leads to a much higher risk of rapid drought-related forest dieback for the late twenty-first century.

If the current trend of failing to meet the targets of the Paris Agreement continues (UNEP 2019), low- to mid-elevation mountain forests may be at particular risk of drought-related tree mortality and substantial losses in their protective function against gravitational hazards. To avoid or at least mitigate this situation, forest management should particularly promote the regeneration with climate-adapted species (SCNAT 2016). Our results demonstrate how a DVM approach can provide decision support in the selection of potentially suitable species and help to estimate the time span remaining for forest management to address these issues before negative changes are becoming evident in the forest. Both aspects, i.e. identifying suitable species and estimating available time windows for taking action, are key for enterprise-level forest planning (Streit et al. 2017). Based on the results from BS, considerable impacts of climate change are likely to be expected in our case study enterprise from around the mid-twenty-first century under a 'high-impact' climate scenario, suggesting that forest management has less than three decades to establish sufficient advance regeneration, which is a critically short time window in mountain forests (Ott et al. 1997).

Besides the direct impacts of climate change on low-elevation sites, abiotic and biotic disturbances by windthrow and bark beetle attacks pose a threat to the spruce forests at higher elevations (Seidl et al. 2011b; Temperli et al. 2013). As demonstrated by our exemplary disturbance simulations, the benefit of timely forest management and reduced browsing pressure also plays a key role for post-disturbance recovery in high-elevation forests. Notably, a higher post-disturbance basal area and a faster recovery were simulated when the disturbance (windthrow or bark beetle) occurred in the late twenty-first century (year 2080), which was due to a higher abundance of advance regeneration induced by management and the additional effect of the warmer climate. These findings are supported by empirical studies, e.g. by Schwitter et al. (2015), who evaluated 24 years of forest dynamics at windthrow sites in Switzerland and found that post-disturbance recovery was much faster when advance regeneration was present in the pre-disturbance stands. This initial advantage in the first years after disturbance is of particular importance for the protection function of a forest, since trees of a certain minimum height are required to provide protection against avalanches and rockfall (Noack et al. 2004). Furthermore, browsing pressure is a key factor that can reduce establishment and slow down post-disturbance forest succession substantially, as shown by various empirical (e.g. Kupferschmid and Bugmann 2005) and modelling studies (e.g. Kupferschmid et al. 2006; Thrippleton et al. 2018). It has to be noted, however, that rather than providing a realistic projection of future forest dynamics under changing disturbance regimes, our exemplary disturbance simulations only aimed to test the broad effects of timing of disturbance, previous management and browsing pressure on recovery. Despite these limitations, our results demonstrate at a general level that reduced browsing pressure and adequate forest management are key to improve forest resilience to disturbances by windthrow and bark beetle attacks in susceptible spruce-dominated mountain forests.

Using DVMs as decision support tools for mountain forest managers

Our study exemplifies how a DVM can provide key insights into climate change impacts at the scale of interest of a forest enterprise. For the present study, a relatively simple approach was applied, which requires only moderate efforts in terms of data acquisition from the forest enterprise (i.e. full calipering of a small number of representative stands). However, DVMs can provide a wealth of further decision support under changing environmental conditions [see also review by Fontes et al. (2010)] from lowland to mountain forests (e.g. Irauschek et al. 2017a; Lexer and Bugmann 2017; Gutsch et al. 2018).

With respect to spatial scale, measurements of current stand structure can be obtained at high resolution and large spatial extents by combining inventory data and airborne laser scanning (LiDAR), as shown by Maroschek et al. (2015). Rather than using the spatially limited approach of representative stands, as in our study, some DVMs are capable of representing the spatial arrangement of forest patches at much larger spatial scales, e.g. the models LANDIS (Mladenoff 2004), iLand (Seidl et al. 2012) or LandClim (Schumacher et al. 2004). This type of landscape models furthermore allows to simulate exogenous disturbances as self-emergent properties of the system (e.g. Seidl et al. 2014; Temperli et al. 2015), which was not possible in our stand-scale DVM. However, the increasing degree of spatial detail comes with its own challenges, e.g. a strongly increasing data demand [see also review by Keane et al. (2015)], which reduces the likelihood of such models being used in the absence of a dedicated and specifically funded research project.

Another aspect that was not investigated in detail in this study is the use of DVMs to explore alternative forest management approaches to optimize the provisioning of multiple goods and services. The capacity of DVMs to assess trade-offs and synergies between multiple ecosystem services has been addressed more recently, e.g. by studies in different mountain areas within Europe by Mina et al. (2017a) and Langner et al. (2017). An overview of the management capacities of different DVMs is given in Fontes et al. (2010), although the capabilities of some DVMs have increased considerably in the last years (e.g. Irauschek et al. 2017b; Mina et al. 2017b). Ultimately, multi-criteria decision analyses can be used in combination with DVM simulations to facilitate the identification of appropriate management alternatives for a wide range of forest goods and services (e.g. Wolfslehner and Seidl 2010).

Overall, DVMs are increasingly suitable tools for providing decision support in mountain forests. A broader coverage of studies from different mountain regions would thus be highly valuable from a forest management perspective as well as from a scientific perspective, e.g. for synthesizing overarching conclusions on the impact of climate change in mountain regions (e.g. Price et al. 2011).

Conclusion

Although climate change impact assessments are increasingly becoming available at larger (e.g. national) scales, only a few studies have focused on the climate change impacts on mountain forests at the level of a forest enterprise, taking into account the combined effect of climate, specific site conditions, initial forest structure and management. Dynamic forest models are capable of accounting for these aspects and thus are promising tools to provide assessments at a relatively high local resolution, which is required by mountain forest managers.

The present study demonstrates how a DVM approach can provide information on site-specific forest vulnerability, assessments of the timing and magnitude of change, quantification of changes in protective function as well as information regarding the choice of climate-adapted tree species; all these aspects are highly relevant for long-term planning within the forest enterprise. For our case study forest enterprise, key conclusions were: (1) low-elevation sites ($\leq$ 1000 m a.s.l.) were most vulnerable to adverse climate change impacts and should thus receive particular attention. (2) Forest management was of high importance to induce sufficient advance regeneration, which is key to ensure forest resilience and specifically the protective function in the long term. (3) Management measures must be taken in the near future (i.e. the coming 20–30 years) to avoid a severe loss of the protective function particularly under a 'high-impact' climate scenario. Although higher-elevation sites benefited from the warming climate, simulations for potential natural vegetation indicate that the current vegetation composition becomes climatically unsuitable, thus suggesting that risks of catastrophic disturbances (e.g. windthrow and bark beetle) may rise accordingly.

Ultimately, the results from this study emphasize that international efforts to reach the goals of the Paris Agreement are of crucial importance for mountain forests, as unabated climate change is likely to severely deteriorate forest health as well as the services that are provided by these forests.

Acknowledgements We thank Dominic Michel for support in all IT-related questions and the employees of the OAK Schwyz for conducting the measurements of forest structure in the field. David I. Forrester and the Experimental Forest Management (EFM) Project of the Swiss Federal Research Institute WSL are gratefully acknowledged for providing data on the current stand structure of the site FW (Riemenstalden). Two anonymous reviewers are gratefully acknowledged for their thoughtful comments and helpful suggestions.

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