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TITLE:

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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KEYWORDS: Mountain forest, climate change impacts, Switzerland, dynamic vegetation model, ungulate browsing.

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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 to 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 21st century at low elevations. A set of exemplary disturbance scenarios (windthrow and bark beetle) demonstrated the importance of forest management and browsing for post-disturbance resilience in 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.

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 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 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 e.g., 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 e.g., 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 subalpine 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 (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., 2017; Huber 2019) 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 to represent (1) the most frequent forest communities (after 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 southeastern part of Lake Lucerne to >2000 mm in the valleys in its east and northeast (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.

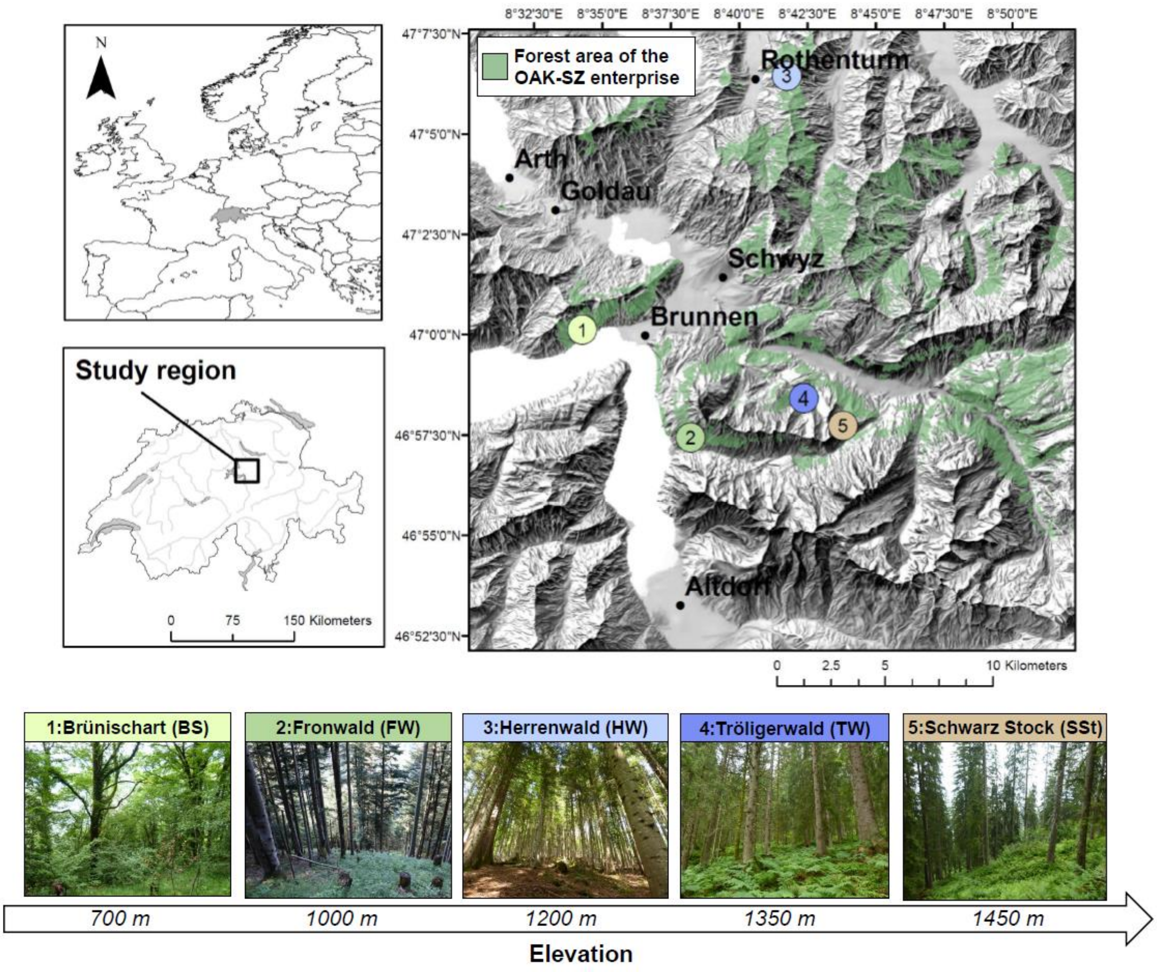

Figure 1 Location of study sites within the management area of the forest enterprise 'Oberallmeindkorporation Schwyz' (OAK-SZ), Switzerland. © Swisstopo.

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 (after 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 & 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

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. 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.

Calculation of ecosystem services

Changes in aboveground biomass, species composition and forest structure were measured in terms of basal area (m^2 ha^{-1}), protection against gravitational hazards was calculated as a 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 is derived from 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 to 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 – 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 of annual precipitation sum by -10% until the end of the 21st century (relative to the baseline period of 1980 to 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), 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 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).

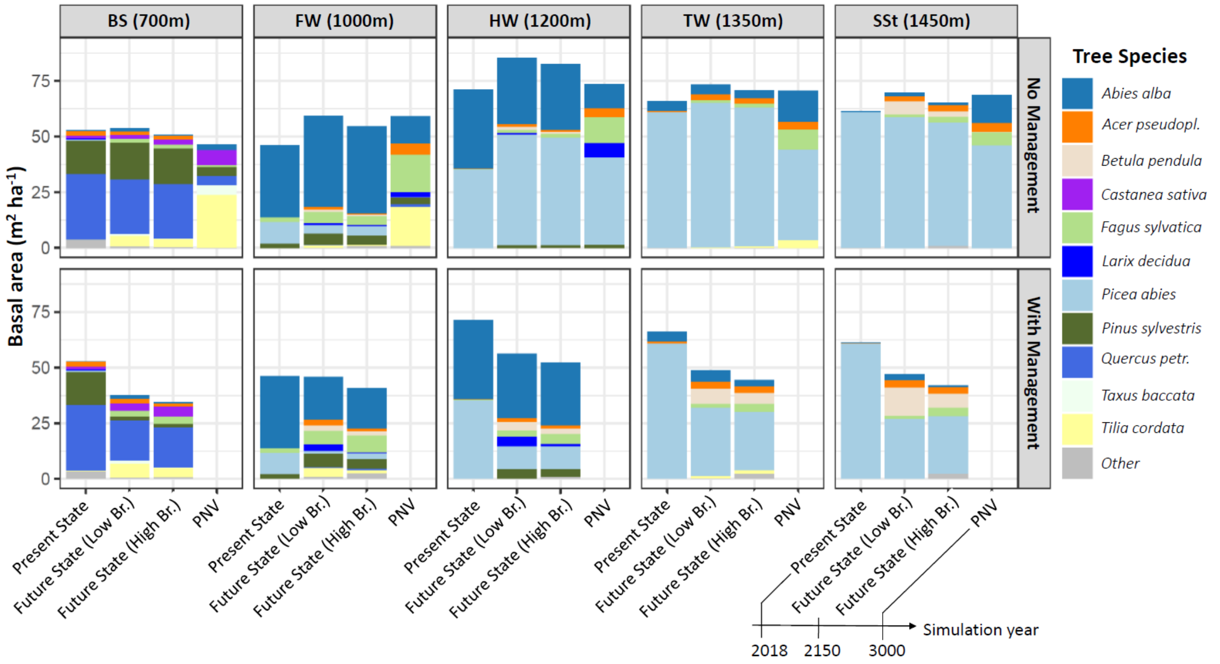

Figure 2 Stand basal area under the 'Low impact' climate scenario (RCP3PD) at the five study sites for unmanaged (top row) and managed (bottom row) conditions. 'Present state' refers to measured initial state at year 2018, 'Future state' (with 'low' and 'high' browsing pressure) refers to stand state 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).

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 silvestris*-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).

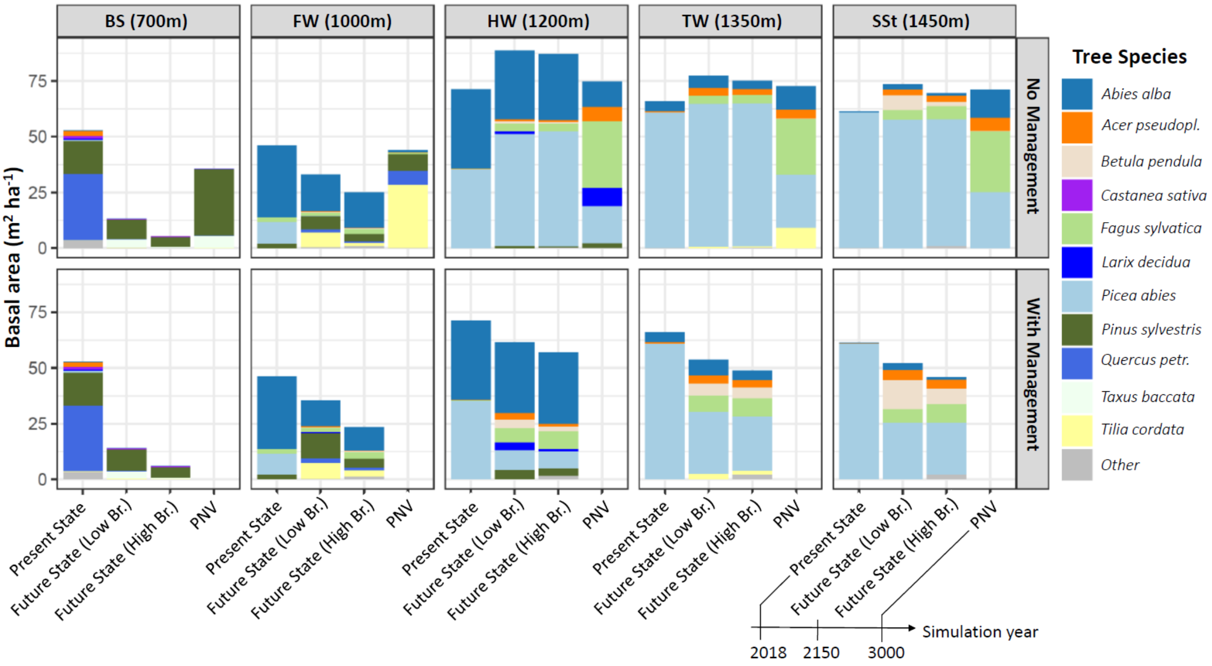

Figure 3 Stand basal area under the 'High impact' climate scenario (A2) at the five study sites for unmanaged (top row) and managed (bottom row) conditions. 'Present state' refers to measured initial state at year 2018, 'Future state' (with 'low' and 'high' browsing pressure) refers to stand state at 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).

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).

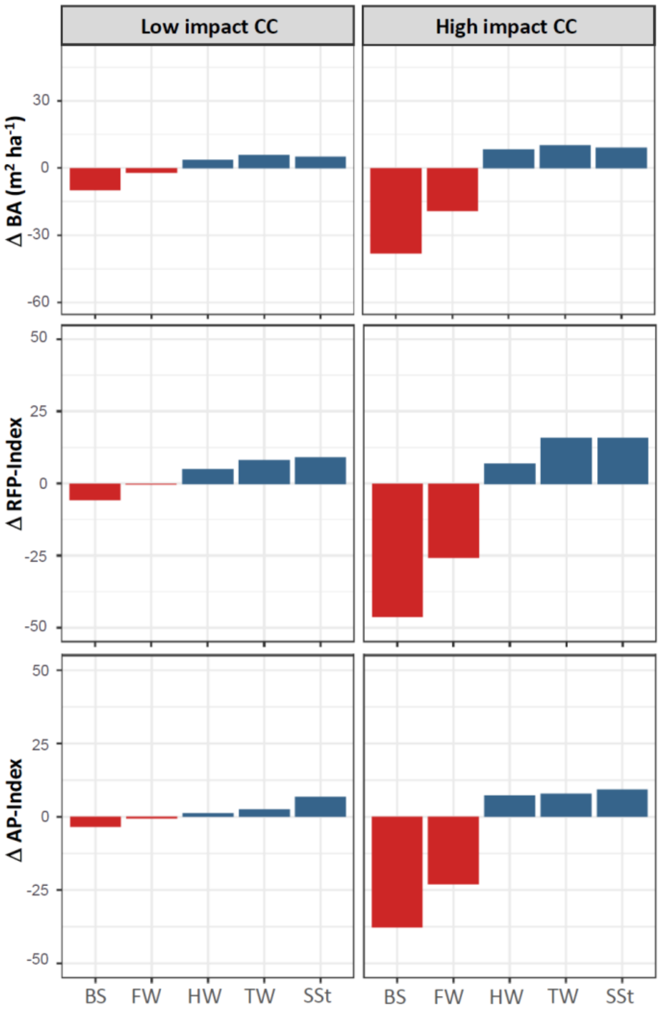

Figure 4 Changes in basal area, rockfall protection (RFP) and avalanche protection (AP) index for all sites at year 2150 under the 'low impact' (RCP3PD) and 'high impact' (A2) scenario relative to present climate. Colours indicate the direction of change (red: decrease, blue: increase). Note that results 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 21st century, and to a smaller extent (Fig.5 and Online Resource 2, Table A2.1, Fig. A2.9).

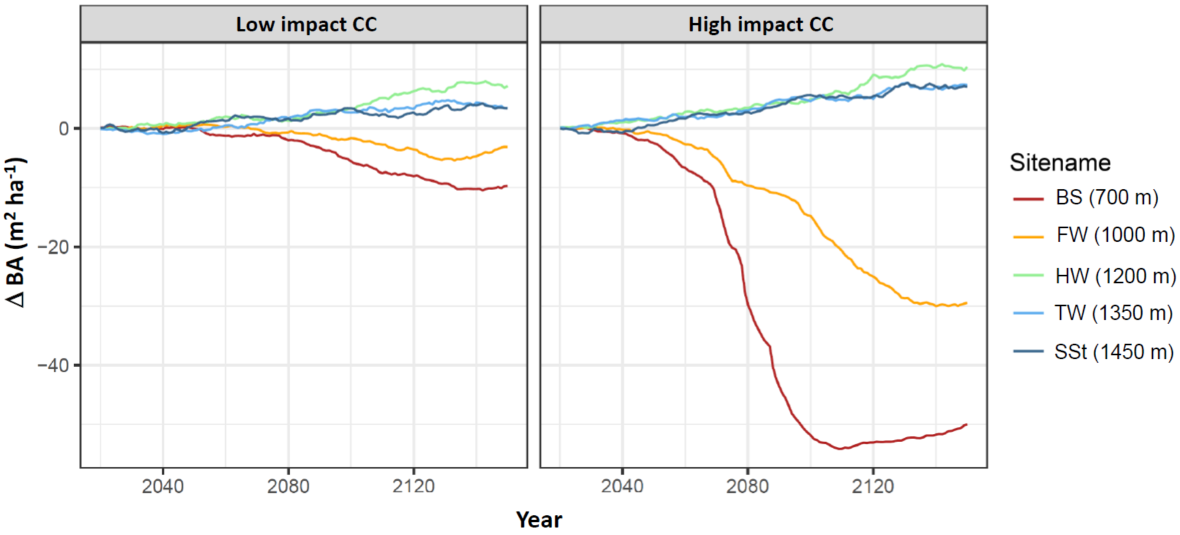

Figure 5 Development of basal area over time under the ‘low impact’ (RCP3PD) and ‘high impact’ (A2) scenario, shown as the difference to the respective trajectory under present climatic conditions for the five study sites under unmanaged conditions.

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 m² per ha (Fig. 6 and Online Resource 3, Fig. A3.26ff.). The reduction of 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).

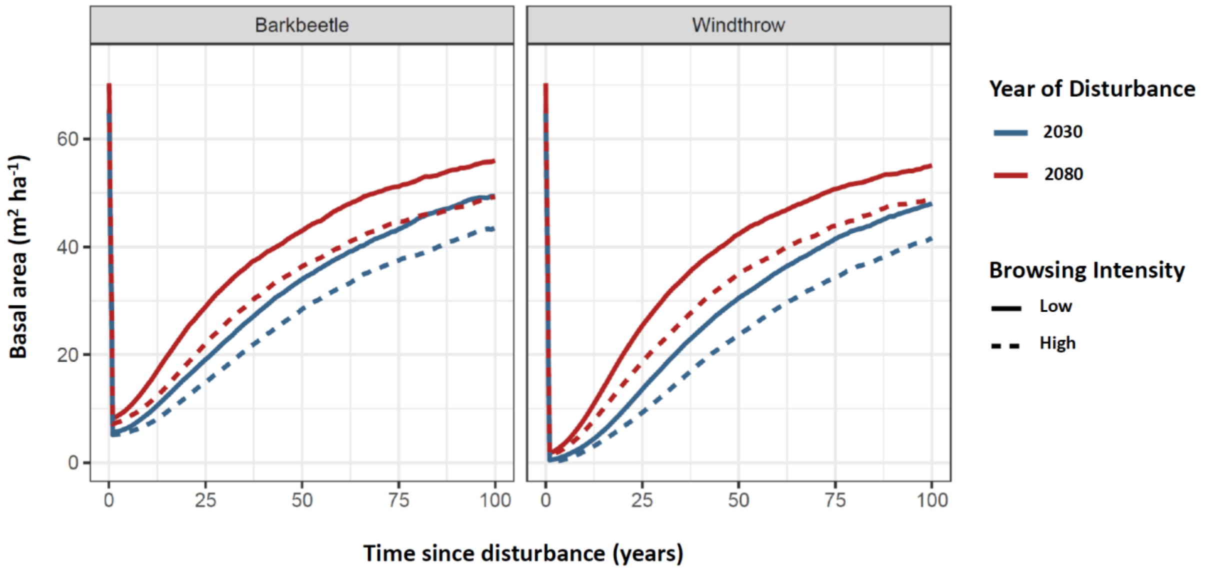

Figure 6 Post-disturbance recovery of basal area for the exemplary barkbeetle and windthrow disturbance scenarios at the site TW (1350 m). Different colors indicate the different time point of disturbance occurrence (2030 or 2080). Different line type indicates the browsing intensity. Simulations assumed a ‘high impact’ (A2) climate change scenario without pre-disturbance management.

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).

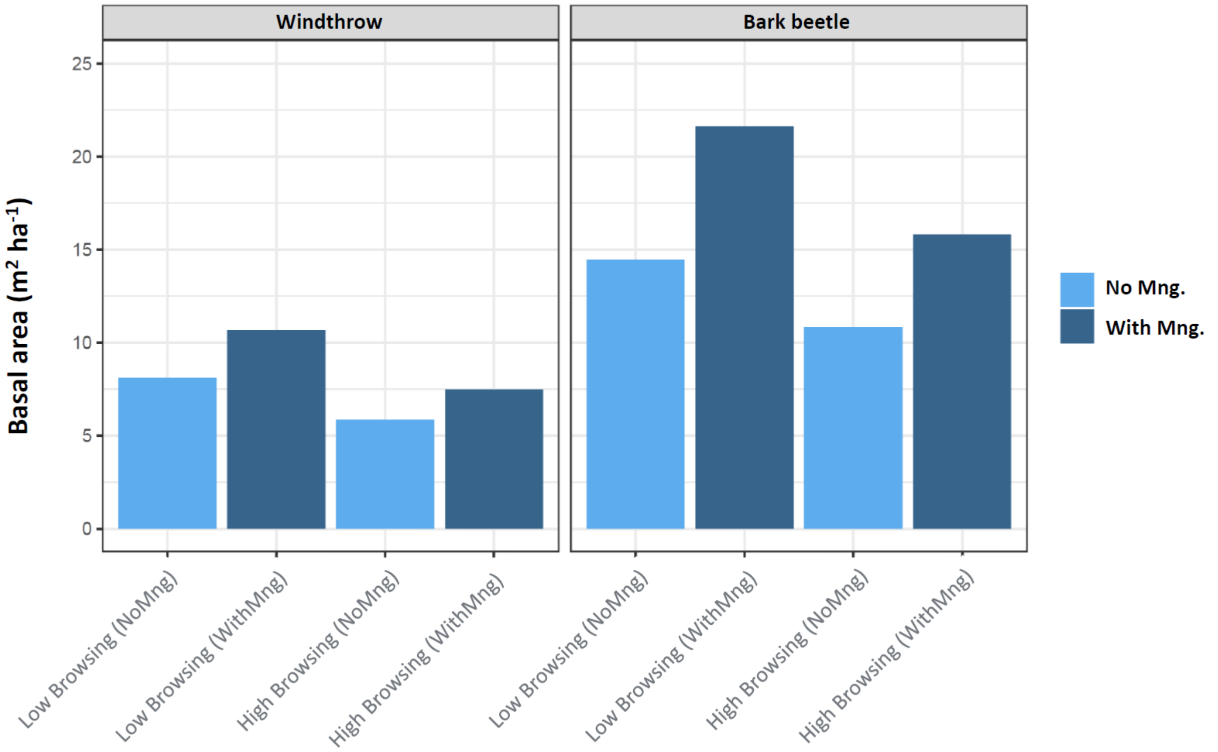

Figure 7 Basal area at the end of the first decade after disturbance in 2080 for the two exemplary disturbance scenarios (windthrow and bark beetle) under low and high browsing, as well as managed ("WithMng") and unmanaged ("NoMng") conditions at the site TW (1350 m). Results for the disturbance in year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

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-21st 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 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, e.g., 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 (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 of 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 21st 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 of *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 21st 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 21st 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 timespan 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-21st 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 was simulated when the disturbance (windthrow or bark beetle) occurred in the late 21st 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 handful 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 (≤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 to 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 barkbeetle) 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.

ELECTRONIC SUPPLEMENTARY MATERIALS:

ESM_1: Extended material and methods

ESM_2: Additional simulation results

ESM_3: Detailed site-specific projections

REFERENCES:

Allen, C. D., D. D. Breshears, and N. G. McDowell. 2015. On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene. Ecosphere **6**:1-55.

Allen, C. D., A. K. Macalady, H. Chenchouni, D. Bachelet, N. McDowell, M. Vennetier, T. Kitzberger, A. Rigling, D. D. Breshears, E. H. Hogg, P. Gonzalez, R. Fensham, Z. Zhang, J. Castro, N. Demidova, J. H. Lim, G. Allard, S. W. Running, A. Semerci, and N. Cobb. 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. Forest Ecology and Management **259**:660-684.

ATRAGENE. 1997. Standortskundliche Erhebungen, Waldbau C-Projekte Gersau, Fallenbach und Sitiwald, Forstkreis 2, Rigi-Rossberg, Kanton Schwyz.

ATRAGENE. 1999. Standortskundliche Erhebungen, Forstkreis 1, Muotathal-Fronalpstock, Kanton Schwyz.

ATRAGENE. 2004. Standortskundliche Erhebungen, Rothenthurm-Rossberg, Kanton Schwyz.

Bauhus, J., K. J. Puettmann, and C. Kühne. 2013. Close-to-nature forest management in Europe. Pages 187-213 *in* C. Messier, K. J. Puettmann, and K. D. Coates, editors. Managing Forests as Complex Adaptive Systems: Building to the Challenge of Global Change. The Earthscan Forest Library, New York.

Bebi, P., H. Bugmann, P. Lüscher, B. Lange, and P. Brang. 2016. Auswirkungen des Klimawandels auf Schutzwald und Naturgefahren. Pages 269-285 *in* A. R. Pluess, S. Augustin, and P. Brang, editors. Wald im Klimawandel. Grundlagen für Adaptationsstrategien. Bundesamt für Umwelt BAFU,Bern, Eidgenössische Forschungsanstalt für Wald,Schnee und Landschaft WSL,Birmensdorf, Bern, Stuttgart, Wien.

Bigler, C., O. U. Braker, H. Bugmann, M. Dobbertin, and A. Rigling. 2006. Drought as an inciting mortality factor in Scots pine stands of the Valais, Switzerland. Ecosystems **9**:330-343.

Bircher, N., M. Cailleret, M. Huber, and H. Bugmann. 2015. Empfindlichkeit typischer Schweizer Waldbestände auf den Klimawandel. Schweizerische Zeitschrift für Forstwesen **166**:408–419.

Botkin, D. B., J. F. Janak, and J. R. Wallis. 1972. Some ecological consequences of a computer model of forest growth. Journal of Ecology **60**:849-872.

Bugmann, H. 1996. A simplified forest model to study species composition along climate gradients. Ecology **77**:2055-2074.

Bugmann, H., P. Brang, C. Elkin, P. Henne, O. Jakoby, M. Levesque, H. Lischke, A. Psomas, A. Rigling, B. Wermelinger, and N. E. Zimmermann. 2014. Climate change impacts on tree species, forest properties and ecosystem services.*in* CH2014-Impacts, editor. Towards Quantitative Scenarios of Climate Change Impacts in Switzerland. OCCR, FOEN, MeteoSwiss, C2SM, Agroscope, and ProClim, Bern, Switzerland.

CH2011. 2011. Swiss Climate Change Scenarios CH2011. C2SM, MeteoSwiss, ETH, NCCR Climate, and OcCC, Zurich, Switzerland.

Condes, S., and M. del Rio. 2015. Climate modifies tree interactions in terms of basal area growth and mortality in monospecific and mixed Fagus sylvatica and Pinus sylvestris forests. European Journal of Forest Research **134**:1095-1108.

Côté, S. D., T. P. Rooney, J. P. Tremblay, C. Dussault, and D. M. Waller. 2004. Ecological impacts of deer overabundance. Annual Review of Ecology Evolution and Systematics **35**:113-147.

Dai, A. G. 2013. Increasing drought under global warming in observations and models. Nature Climate Change **3**:52-58.

Didion, M., A. D. Kupferschmid, A. Wolf, and H. Bugmann. 2011. Ungulate herbivory modifies the effects of climate change on mountain forests. Climatic Change **109**:647-669.

Dorren, L., F. Berger, and B. Maier. 2005. Der Schutzwald als Steinschlagnetz. LWF aktuell **50**:25-27.

EEA. 2010. Europe’s Ecological Backbone: Recognising the True Value of Our Mountains. European Environment Agency, Copenhagen.

Elkin, C., A. G. Gutierrez, S. Leuzinger, C. Manusch, C. Temperli, L. Rasche, and H. Bugmann. 2013. A 2 degrees C warmer world is not safe for ecosystem services in the European Alps. Global Change Biology **19**:1827-1840.

Ellenberg, H., and F. Klötzli. 1972. Waldgesellschaften und Waldstandorte der Schweiz. Schweizerische Anstalt für das Forstliche Versuchswesen, Birmensdorf, ZH.

Etzold, S., K. Zieminska, B. Rohner, A. Bottero, A. K. Bose, N. K. Ruehr, A. Zingg, and A. Rigling. 2019. One Century of Forest Monitoring Data in Switzerland Reveals Species- and Site-Specific Trends of Climate-Induced Tree Mortality. Frontiers in Plant Science **10**.

Fontes, L., J. D. Bontemps, H. Bugmann, M. Van Oijen, C. Gracia, K. Kramer, M. Lindner, T. Rotzer, and J. P. Skovsgaard. 2010. Models for supporting forest management in a changing environment. Forest Systems **19**:8-29.

Forrester, D. I., C. Ammer, P. J. Annighofer, A. Avdagic, I. Barbeito, K. Bielak, G. Brazaitis, L. Coll, M. del Rio, L. Drossler, M. Heym, V. Hurt, M. Lof, B. Matovic, F. Meloni, J. den Ouden, M. Pach, M. G. Pereira, Q. Ponette, H. Pretzsch, J. Skrzyszewski, D. Stojanovic, M. Svoboda, R. Ruiz-Peinado, G. Vacchiano, K. Verheyen, T. Zlatanov, and A. Bravo-Oviedo. 2017. Predicting the spatial and temporal dynamics of species interactions in Fagus sylvatica and Pinus sylvestris forests across Europe. Forest Ecology and Management **405**:112-133.

Forrester, D. I., J. Nitzsche, and H. Schmid. 2019. The Experimental Forest Management project: An overview and methodology of the long-term growth and yield plot network. Swiss Federal Institute of Forest, Snow and Landscape Research WSL, Birmensdorf.

Frank, A., G. T. Howe, C. Sperisen, P. Brang, J. B. St Clair, D. R. Schmatz, and C. Heiri. 2017. Risk of genetic maladaptation due to climate change in three major European tree species. Global Change Biology **23**:5358-5371.

Frehner, M., B. Wasser, and R. Schwitter. 2005. Nachhaltigkeit im Schutzwald (Projekt NaiS) - Bundesamt für Umwelt BAFU. Bern.

Gazda, A., P. Koscielniak, M. Hardy, E. Muter, K. Kedra, J. Bodziarczyk, M. Fraczek, K. Chwistek, W. Rozanski, and J. Szwagrzyk. 2019. Upward expansion of distribution ranges of tree species: Contrasting results from two national parks in Western Carpathians. Science of the Total Environment **653**:920-929.

Gutsch, M., P. Lasch-Born, C. Kollas, F. Suckow, and C. P. O. Reyer. 2018. Balancing trade-offs between ecosystem services in Germany's forests under climate change. Environmental Research Letters **13**:1-12.

Gutierrez, A., R.S. Snell, H. Bugmann (2016) Using a dynamic forest model to predict tree species distributions. Global Ecol Biogeogr 25:347–358

HADES. 2015. Hydrologischer Atlas der Schweiz. University of Bern, Bern, Switzerland.

Hantke, R., and E. Kuriger. 2003. Überblick über die Geologie des Kantons Schwyz und seiner Nachbargebiete. Pages 9-17 *in* SCNAT, editor. Geologie und Geotope im Kanton Schwyz. Schwyzerische Naturforschende Gesellschaft, Einsiedeln.

Huber, N. 2019. Towards robust projections of future forest dynamics: why there is no silver bullet to cope with complexity. PhD Thesis, ETH Zurich.

IPCC. 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Irauschek, F., W. Rammer, and M. J. Lexer. 2017a. Can current management maintain forest landscape multifunctionality in the Eastern Alps in Austria under climate change? Regional Environmental Change **17**:33-48.

Irauschek, F., W. Rammer, and M. J. Lexer. 2017b. Evaluating multifunctionality and adaptive capacity of mountain forest management alternatives under climate change in the Eastern Alps. European Journal of Forest Research **136**:1051-1069.

Jump, A. S., J. M. Hunt, and J. Penuelas. 2006. Rapid climate change-related growth decline at the southern range edge of Fagus sylvatica. Global Change Biology **12**:2163-2174.

Keane, R. E., D. McKenzie, D. A. Falk, E. A. H. Smithwick, C. Miller, and L. K. B. Kellogg. 2015. Representing climate, disturbance, and vegetation interactions in landscape models. Ecological Modelling **309**:33-47.

Klopcic, M., M. Mina, H. Bugmann, and A. Boncina. 2017. The prospects of silver fir (Abies alba Mill.) and Norway spruce (Picea abies (L.) Karst) in mixed mountain forests under various management strategies, climate change and high browsing pressure. European Journal of Forest Research **136**:1071-1090.

Kupferschmid, A. D., P. Brang, W. Schonenberger, and H. Bugmann. 2006. Predicting tree regeneration in Picea abies snag stands. European Journal of Forest Research **125**:163-179.

Kupferschmid, A. D., and H. Bugmann. 2005. Effect of microsites, logs and ungulate browsing on Picea abies regeneration in a mountain forest. Forest Ecology and Management **205**:251-265.

Kupferschmid, A. D., C. Heiri, M. Huber, M. Fehr, M. Frei, P. Gmür, N. Imesch, J. Zinggeler, P. Brang, J.-C. Clivaz, and O. Odermatt. 2015. Einfluss wildlebender Huftiere auf die Waldverjüngung: ein Überblick für die Schweiz. Schweizerische Zeitschrift für Forstwesen **166**:420-431.

Lafond, V., G. Lagarrigues, T. Cordonnier, and B. Courbaud. 2014. Uneven-aged management options to promote forest resilience for climate change adaptation: effects of group selection and harvesting intensity. Annals of Forest Science **71**:937-937.

Langner, A., F. Irauschek, S. Perez, M. Pardos, T. Zlatanov, K. Ohman, E. M. Nordstrom, and M. J. Lexer. 2017. Value-based ecosystem service trade-offs in multi-objective management in European mountain forests. Ecosystem Services **26**:245-257.

Leuch, B. A., K. Streit, and P. Brang. 2017. Naturnaher Waldbau im Klimawandel. Merkblatt für die Praxis **59**:1-8.

Leuschner, C., and I. C. Meier. 2018. The ecology of Central European tree species: Trait spectra, functional trade-offs, and ecological classification of adult trees. Perspectives in Plant Ecology Evolution and Systematics **33**:89-103.

Levesque, M., M. Saurer, R. Siegwolf, B. Eilmann, P. Brang, H. Bugmann, and A. Rigling. 2013. Drought response of five conifer species under contrasting water availability suggests high vulnerability of Norway spruce and European larch. Global Change Biology **19**:3184-3199.

Lexer, M. J., and H. Bugmann. 2017. Mountain forest management in a changing world. European Journal of Forest Research **136**:981-982.

Lexer, M. J., K. Honninger, H. Scheifinger, C. Matulla, N. Groll, H. Kromp-Kolb, K. Schadauer, F. Starlinger, and M. Englisch. 2002. The sensitivity of Austrian forests to scenarios of climatic change: a large-scale risk assessment based on a modified gap model and forest inventory data. Forest Ecology and Management **162**:53-72.

Lindner, M., M. Maroschek, S. Netherer, A. Kremer, A. Barbati, J. Garcia-Gonzalo, R. Seidl, S. Delzon, P. Corona, M. Kolstrom, M. J. Lexer, and M. Marchetti. 2010. Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. Forest Ecology and Management **259**:698-709.

Maroschek, M., W. Rammer, and M. J. Lexer. 2015. Using a novel assessment framework to evaluate protective functions and timber production in Austrian mountain forests under climate change. Regional Environmental Change **15**:1543-1555.

Mina, M., H. Bugmann, T. Cordonnier, F. Irauschek, M. Klopcic, M. Pardos, and M. Cailleret. 2017a. Future ecosystem services from European mountain forests under climate change. Journal of Applied Ecology **54**:389-401.

Mina, M., H. Bugmann, M. Klopcic, and M. Cailleret. 2017b. Accurate modeling of harvesting is key for projecting future forest dynamics: a case study in the Slovenian mountains. Regional Environmental Change **17**:49-64.

Minerbi, S., A. Cescatti, P. Cherubini, K. Hellrigl, G. Markart, M. Saurer, and C. Mutinelli. 2006. Scots Pine dieback in the Isarco Valley due to severe drought in the summer of 2003. Forest Observer **2**:89-144.

Mladenoff, D. J. 2004. LANDIS and forest landscape models. Ecological Modelling **180**:7-19.

Noack, A., W. Schönenberger, and P. Thee. 2004. Schützen Windwurfflächen vor Lawinen und Steinschlag? Wald und Holz **10**:43-46.

Ott, E., M. Frehner, H. U. Frey, and P. Lüscher. 1997. Gebirgsnadelwälder: ein praxisorientierter Leitfaden für eine standortgerechte Waldbehandlung. P. Haupt Verlag, Bern, Switzerland.

Penuelas, J., and M. Boada. 2003. A global change-induced biome shift in the Montseny mountains (NE Spain). Global Change Biology **9**:131-140.

Pretzsch, H., R. Grote, B. Reineking, T. Roetzer, and S. Seifert. 2008. Models for forest ecosystem management: A European perspective. Annals of Botany **101**:1065-1087.

Price, M. F., G. Gratzer, L. A. Duguma, T. Kohler, D. Maselli, and R. Romeo. 2011. Mountain Forests in a Changing World - Realizing Values, addressing challenges., Food and Agriculture Organization of the United Nations, FAO, Rome.

R Development Core Team. 2017. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Radtke, A., D. Toe, F. Berger, S. Zerbe, and F. Bourrier. 2014. Managing coppice forests for rockfall protection: lessons from modeling. Annals of Forest Science **71**:485-494.

Rasche, L., L. Fahse, A. Zingg, and H. Bugmann. 2011. Getting a virtual forester fit for the challenge of climatic change. Journal of Applied Ecology **48**:1174-1186.

Rasche, L., L. Fahse, A. Zingg, and H. Bugmann. 2012. Enhancing gap model accuracy by modeling dynamic height growth and dynamic maximum tree height. Ecological Modelling **232**:133-143.

Reyer, C. P. O., N. Brouwers, A. Rammig, B. W. Brook, J. Epila, R. F. Grant, M. Holmgren, F. Langerwisch, S. Leuzinger, W. Lucht, B. Medlyn, M. Pfeifer, J. Steinkamp, M. C. Vanderwel, H. Verbeeck, and D. M. Villela. 2015. Forest resilience and tipping points at different spatio-temporal scales: approaches and challenges. Journal of Ecology **103**:5-15.

Rigling, A., C. Bigler, B. Eilmann, E. Feldmeyer-Christe, U. Gimmi, C. Ginzler, U. Graf, P. Mayer, G. Vacchiano, P. Weber, T. Wohlgemuth, R. Zweifel, and M. Dobbertin. 2013. Driving factors of a vegetation shift from Scots pine to pubescent oak in dry Alpine forests. Global Change Biology **19**:229-240.

Sanchez-Salguero, R., J. C. Linares, J. J. Camarero, J. Madrigal-Gonzalez, A. Hevia, A. Sanchez-Miranda, J. A. Ballesteros-Canovas, R. Alfaro-Sanchez, A. I. Garcia-Cervigon, C. Bigler, and A. Rigling. 2015. Disentangling the effects of competition and climate on individual tree growth: A retrospective and dynamic approach in Scots pine. Forest Ecology and Management **358**:12-25.

Schuler, L. J., H. Bugmann, G. Petter, and R. S. Snell. 2019. How multiple and interacting disturbances shape tree diversity in European mountain landscapes. Landscape Ecology **34**:1279–1294.

Schulze, E. D., O. Bouriaud, J. Waldchen, N. Eisenhauer, H. Walentowski, C. Seele, E. Heinze, U. Pruschitzki, G. Danila, G. Marin, D. Hessenmoller, L. Bouriaud, and M. Teodosiu. 2014. Ungulate browsing causes species loss in deciduous forests independent of community dynamics and silvicultural management in Central and Southeastern Europe. Annals of Forest Research **57**:267-288.

Schmid, U. 2014. Bewirtschaftung ausgewählter Wälder der Schweiz unter Klimawandel. Master-Thesis. ETH Zurich, Zurich

Schumacher, S., H. Bugmann, and D. Mladenoff. 2004. Improving the formulation of tree growth and succession in a spatially explicit landscape model. Ecological Modelling **180**:175-194.

Schwitter, R. 2006. Behandlung von Jungwaldbeständen auf Sturmflächen im Schutzwald unter Berücksichtigung der langfristigen Entwicklung. Schweizerische Gebirgswaldpflegegruppe (GWG), Schwyz and Maienfeld.

Schwitter, R. 2013. Gebirgswald- und Schutzwaldpflege: Eine Orientierungshilfe für die Praxis., ibW Bildungszentrum Wald, Maienfeld, Fachstelle für Gebirgswald (GWP).

Schwitter, R., A. Sandri, P. Bebi, T. Wohlgemuth, and P. Brang. 2015. Lehren aus Vivian für den Gebirgswald - im Hinblick auf den nächsten Sturm. Schweizerische Zeitschrift für Forstwesen **166**:159-167.

Schwörer, C., P. D. Henne, and W. Tinner. 2014. A model-data comparison of Holocene timberline changes in the Swiss Alps reveals past and future drivers of mountain forest dynamics. Global Change Biology **20**:1512-1526.

SCNAT. 2016. Brennpunkt Klima Schweiz. Grundlagen, Folgen und Perspektiven. Swiss Academy of Sciences, Bern, Switzerland.

Seidl, R., W. Rammer, and K. Blennow. 2014. Simulating wind disturbance impacts on forest landscapes: Tree-level heterogeneity matters. Environmental Modelling & Software **51**:1-11.

Seidl, R., W. Rammer, and M. J. Lexer. 2011a. Climate change vulnerability of sustainable forest management in the Eastern Alps. Climatic Change **106**:225-254.

Seidl, R., W. Rammer, R. M. Scheller, and T. A. Spies. 2012. An individual-based process model to simulate landscape-scale forest ecosystem dynamics. Ecological Modelling **231**:87-100.

Seidl, R., M. J. Schelhaas, and M. J. Lexer. 2011b. Unraveling the drivers of intensifying forest disturbance regimes in Europe. Global Change Biology **17**:2842-2852.

Seidl, R., D. Thom, M. Kautz, D. Martin-Benito, M. Peltoniemi, G. Vacchiano, J. Wild, D. Ascoli, M. Petr, J. Honkaniemi, M. J. Lexer, V. Trotsiuk, P. Mairota, M. Svoboda, M. Fabrika, T. A. Nagel, and C. P. O. Reyer. 2017. Forest disturbances under climate change. Nature Climate Change **7**:395-402.

Streit, K., B. A. Leuch, and P. Brang. 2017. Der richtige Eingriff zur richtigen Zeit. Wald und Holz **98**:32-35.

Temperli, C., H. Bugmann, and C. Elkin. 2012. Adaptive management for competing forest goods and services under climate change. Ecological Applications **22**:2065-2077.

Temperli, C., H. Bugmann, and C. Elkin. 2013. Cross-scale interactions among bark beetles, climate change, and wind disturbances: a landscape modeling approach. Ecological Monographs **83**:383-402.

Temperli, C., T. T. Veblen, S. J. Hart, D. Kulakowski, and A. J. Tepley. 2015. Interactions among spruce beetle disturbance, climate change and forest dynamics captured by a forest landscape model. Ecosphere **6**:1-20.

Thöle, L., C. Schwörer, D. Colombaroli, E. Gobet, P. Kaltenrieder, J. van Leeuwen, and W. Tinner. 2016. Reconstruction of Holocene vegetation dynamics at Lac de Bretaye, a high-mountain lake in the Swiss Alps. Holocene **26**:380-396.

Thornton, P. E., S. W. Running, and M. A. White. 1997. Generating surfaces of daily meteorological variables over large regions of complex terrain. Journal of Hydrology **190**:214-251.

Thrippleton, T., H. Bugmann, and R. S. Snell. 2018. Herbaceous competition and browsing may induce arrested succession in central European forests. Journal of Ecology **106**:1120-1132.

UNEP. 2019. Emissions Gap Report 2019. Executive summary., United Nations Environment Programme, Nairobi.

Vitasse, Y., G. Hoch, C. F. Randin, A. Lenz, C. Kollas, and C. Korner. 2012. Tree recruitment of European tree species at their current upper elevational limits in the Swiss Alps. Journal of Biogeography **39**:1439-1449.

Watt, A. S. 1947. Pattern and Process in the Plant Community. Journal of Ecology **35**:1-22.

Whiteman, D. C. 2000. Mountain meteorology : fundamentals and applications. Oxford University Press, New York.

Wohlgemuth, T., V. Doublet, C. Nussbaumer, L. Feichtinger, and A. Rigling. 2018. Baumartenwechsel in den Walliser Waldföhrenwäldern verstärkt nach grossen Störungen. Schweizerische Zeitschrift für Forstwesen **169**:260-268.

Wohlgemuth, T., and B. Moser. 2018. Ten years of vegetation dynamics in a forest fire patch in Leuk (Valais). Schweizerische Zeitschrift für Forstwesen **169**:279 - 289.

Wolfslehner, B., and R. Seidl. 2010. Harnessing Ecosystem Models and Multi-Criteria Decision Analysis for the Support of Forest Management. Environmental Management **46**:850-861.

Yousefpour, R., C. Temperli, J. B. Jacobsen, B. J. Thorsen, H. Meilby, M. J. Lexer, M. Lindner, H. Bugmann, J. G. Borges, J. H. N. Palma, D. Ray, N. E. Zimmermann, S. Delzon, A. Kremer, K. Kramer, C. P. O. Reyer, P. Lasch-Born, J. Garcia-Gonzalo, and M. Hanewinkel. 2017. A framework for modeling adaptive forest management and decision making under climate change. Ecology and Society **22**:1-14.

Zou, C. B., G. A. Barron-Gafford, and D. D. Breshears. 2007. Effects of topography and woody plant canopy cover on near-ground solar radiation: Relevant energy inputs for ecohydrology and hydropedology. Geophysical Research Letters **34**:1-6.