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

**Journal Article** 

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2 Climate change impacts across a large forest enterprise in the Northern Pre-Alps - dynamic

3 forest modelling as a tool for decision support

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

18

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### 27 **ABSTRACT**:

Mountain forest managers face the challenge to anticipate climate change (CC) impacts across 28 large elevational ranges. For management planning, information on site-specific long-term 29 responses to CC as well as the consequences for protection functions is particularly crucial. We 30 used the process-based model ForClim to provide projections of forest development and their 31 32 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 33 high-impact CC) at five representative sites along an elevational gradient (700 to 1450 m a.s.l.). 34 35 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) 36 37 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 38 in particular Tilia ('low impact' CC) and Pinus sylvestris ('high impact' CC). Forest 39 management accelerated the shift towards climate-adapted tree species, thereby reducing 40 detrimental effects of the 'low-impact' CC scenario. Under the 'high-impact' scenario, 41 however, drastic decreases in protective function occurred for the late 21<sup>st</sup> century at low 42 elevations. A set of exemplary disturbance scenarios (windthrow and bark beetle) demonstrated 43 44 the importance of forest management and browsing for post-disturbance resilience in mountain 45 forests.

46 Overall, our results underline the potential of process-based forest models as decision support
47 tools for forest enterprises, providing local projections of CC impacts across large elevational
48 ranges at the site-specific resolution required by forest managers.

#### 50 **INTRODUCTION:**

51 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 52 53 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). 54 Maintaining the multitude of ES under climate change is particularly important for mountain 55 forests, which provide important ES for the mountain regions themselves (e.g., protection 56 functions against gravitational hazards, Elkin et al. 2013, Irauschek et al. 2017a) as well as 57 downstream (EEA 2010, Langner et al. 2017). 58

Climate change impacts on mountain forests can be highly heterogeneous in space, i.e. varying 59 in particular with elevation and local topography (Lindner et al. 2010). While low-elevation 60 valley bottoms are likely to become increasingly prone to drought-induced forest die-off (e.g., 61 Bigler et al. 2006, Jump et al. 2006), higher elevations on the contrary tend to benefit from 62 longer vegetation periods and thus better growing conditions (Lindner et al. 2010, Bugmann et 63 al. 2014). However, high spatial heterogeneity (e.g., in terms of topography) and local site and 64 stand conditions (e.g., soil conditions, species composition) can superimpose these larger-scale 65 trends (Lindner et al. 2010) and potentially lead to complex, site-specific forest responses to 66 climate change (e.g., Etzold et al. 2019). Previous studies providing climate impact assessments 67 for mountain forest managers therefore emphasized the importance of local site and stand 68 conditions at a relatively fine scale and high resolution (Irauschek et al. 2017a, Klopcic et al. 69 70 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 75 76 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 77 (Forrester et al. 2017). Furthermore, various DVMs have been expanded over the last years to 78 79 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 80 suitability of DVMs to assess the effect of management and climate change on future forest 81 development and ecosystem service provisioning in a mountain context (e.g., Maroschek et al. 82 2015, Mina et al. 2017a). 83

In spite of the availability of assessments at larger (e.g., national) scales (e.g., Lexer et al. 2002, 84 Bircher et al. 2015), still only few studies are available for mountain forests at the local scale, 85 providing decision support at the level required by an individual forest enterprise (see e.g., 86 Maroschek et al. 2015). Furthermore, findings from one case study area may apply only to a 87 limited degree to another area, particularly if environmental conditions are markedly different 88 89 (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 90 they may therefore benefit significantly from DVM assessments that account for the specific 91 92 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 100 101 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 102 consequences for the forests' protection function (Elkin et al. 2013, Bebi et al. 2016). An aspect 103 104 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 105 106 (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 107 overstorey disturbances (e.g., bark beetle outbreaks, Temperli et al. 2013, Seidl et al. 2017) as 108 109 well as intensified browsing pressure due to high ungulate populations (Côté et al. 2004, 110 Schulze et al. 2014).

The purpose of this study is therefore to address a set of stakeholder-defined management 111 questions at a high local resolution within the forest enterprise, which thus complements larger-112 scale assessments (Bircher et al. 2015) and results from local-scale studies from other mountain 113 114 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 115 furthermore provides an informative case for other managed mountain forests in the Northern 116 Alps, where contrasting climate change impacts can be expected to occur along elevational 117 gradients (cf. Lexer and Bugmann 2017). 118

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 speciescomposition for two contrasting climate change scenarios ('low' and 'high impact')?

(2) *When* are changes in structure and composition to be expected? Are these changesgradual or abrupt?

127 (3) Which effect will large-scale disturbances (windthrow, bark beetles) have at spruce 128 dominated sites under a 'high impact' climate scenario? How is post-disturbance
 129 recovery affected by previous forest management and the level of ungulate browsing?

130

# 131 METHODS:

### 132 Forest model ForClim

ForClim is a climate-sensitive dynamic vegetation model developed for short- and long-term 133 134 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 135 influence of site-specific environmental conditions (e.g., temperature, precipitation, 136 topography, soil conditions, etc.). A forest is represented by multiple small patches, with the 137 patch size equivalent to the area dominated by a single large tree individual (Botkin et al. 1972) 138 139 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 140 tree cohorts (i.e., groups of trees of the same species and age, Bugmann, 1996). Environmental 141 142 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, 143 2001). 144

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.

152

153 *Study areas* 

154 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 155 (after Ellenberg and Klötzli 1972) per elevation zone (see Table 1) which were characteristic 156 for the forest enterprise, and (2) stands in the timber stage of development (i.e. dominant DBH 157 > 30 cm), which had highest priority from a forest management perspective. The study region 158 is located in the Northern Alps and features a pronounced precipitation gradient over a relatively 159 short distance, ranging from moderate annual precipitation amounts of ca. 1100 mm at the 160 southeastern part of Lake Lucerne to >2000 mm in the valleys in its east and northeast (HADES 161 2015). Furthermore, soil conditions differ considerably among the sites due to distinct 162 163 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 164 holding capacity (SWHC) due to steep slopes and shallow soil depth on calcareous bedrock 165 (Hantke and Kuriger 2003), deeper soils with a higher SWHC occur at higher elevations, i.e. 166 the study site of Herrenwald (HW), Tröliger Wald (TW) and Schwarz Stock (SSt, see Table 1). 167 In terms of species composition, the lowest elevation site BS is characterized by a broadleaf-168 dominated forest, while the higher elevation sites are dominated by coniferous species 169 170 (particularly Abies alba and Picea abies, see Table 1 for details). The stand structure of each 171 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 172 Experimental Forest Management project under the lead of David I. Forrester (Forrester et al. 173 174 2019). Details about the stand initialisation are provided in Online Resource 1.



Elevation

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	Ν	Brown soil	80	PiAbie	46D
Schwarz Stock (SSt)	1450	sub-alpine	4.42	2033	>30	Ν	Podzol	70	PiAbie	578

#### 180 Small-scale 'mountain forest plentering' silviculture

181 Forest management in mountain regions is particularly difficult, since management options become increasingly constrained towards higher elevations and promoting sufficient 182 183 regeneration is a considerable challenge (Schwitter, 2013). The management technique of 'mountain forest plentering' (MFP) silviculture has been developed to cope with the specific 184 situation in mountain forests, in particular to induce regeneration (Schwitter 2013, Leuch et al. 185 2017). MFP represents a small-scale removal of collectives of trees (rather than individual trees 186 as done in lowland plenter forests, Schwitter 2013) with the objective to foster regeneration via 187 improved light and temperature conditions at the forest floor (Leuch et al. 2017). 188

A new MFP management module was therefore designed for ForClim to harvest tree collectives 189 in small patches of 400 m<sup>2</sup> (i.e. the ForClim patch size in this study) within the forest. Although 190 not being spatially explicit, this routine mimics the approach underlying cable yarding, where 191 the goal is to remove a pre-defined fraction of the standing volume per stand. The harvest 192 intensity is therefore defined as the target timber volume (Vol<sub>Target</sub>), representing the fraction of 193 volume within the entire stand (i.e., all patches) to be harvested per intervention. Besides, a 194 species-specific target diameter  $(DBH_{Target})$  has to be defined by the user, representing the 195 196 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 197 scheduled harvest interventions are only carried out if sufficient harvestable volume (i.e. the 198 prescribed Vol<sub>Target</sub>) is available in the entire stand (i.e. all patches) to mimic the situation that 199 expensive mountain forest harvest interventions are only conducted if the intervention is cost-200 effective, i.e. sufficient timber can be harvested. If sufficient harvestable timer is available for 201 202 the intervention, the module progressively harvests all trees within randomly chosen patches above the user-defined DBH<sub>Target</sub>, thus creating gaps with favourable light conditions for 203 regeneration while not removing the regeneration that is present already (if any; so-called 204

"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 209 210 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 211 along the elevation gradient. For the lower-elevation sites, all interventions were carried out 212 with the same management intensity (Vol<sub>Target</sub> of 15%) for all harvest interventions, applying a 213 214 DBH<sub>Target</sub> 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<sub>Target</sub> of 215 216 25%), followed by lower intensity harvests ( $Vol_{Target}$  of 15%) in the subsequent interventions. At the high elevations, a DBH<sub>Target</sub> of 12 cm was defined for all species. 217

218

# 219 Calculation of ecosystem services

Changes in aboveground biomass, species composition and forest structure were measured in 220 221 terms of basal area (m<sup>2</sup> ha<sup>-1</sup>), protection against gravitational hazards was calculated as a dimensionless protection indices, i.e. avalanche protection index (API) and rockfall protection 222 index (RFPI), developed by Elkin et al. (2013) and Schmid (2014) based on Frehner et al. 223 224 (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 225 226 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 227 RFPI is based on stem density and diameter distribution, which determines the capacity of the 228 229 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.

233

### 234 Simulation scenarios

235 Simulations of future forest dynamics were conducted for present climate and two contrasting 236 climate change scenarios that represented a 'low impact' scenario (RCP3PD, compliant to the 237 targets of the Paris Agreement) and a 'high impact' scenario (A2, i.e. unabated emissions), 238 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 239 using DAYMET (Thornton et al. 1997) was applied (cf. Online Resource 1). The 'low impact' 240 scenario features a moderate increase in annual mean temperature by +1.5 °C and decrease of 241 annual precipitation sum by -10% until the end of the 21<sup>st</sup> century (relative to the baseline period 242 243 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 244 scenarios are provided in Online Resource 1. 245

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 254 255 150 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 256 natural vegetation (PNV) at each site were conducted to provide additional information on this 257 'natural reference state' for forest management. These simulations were run for 1000 years 258 259 under all climate scenarios, in the absence of management, and under a low browsing pressure. 260 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 261 timing of disturbance occurrence is practically impossible (Mina et al. 2017b), we investigated 262 263 forest dynamics following a set of exemplary large-scale disturbances by windthrow and bark-264 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-265 266 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, 267 exemplary disturbance scenarios were simulated under the 'high impact' climate change 268 scenario for the years 2030 and 2070 with and without pre-disturbance management (cf. Online 269 270 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).

### 276 **RESULTS:**

277 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  $\leq 1000$  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.

285 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 286 broadleaved species in the regeneration layer (e.g., Fagus and Acer, Online Resource 3, Fig. 287 A3.14ff.), representing an earlier transition towards a species composition in equilibrium with 288 289 climate (see PNV results). However, this transition in the regeneration layer was inhibited by 290 high browsing pressure (Fig. 2, 'high browsing pressure'; cf. Online Resource 3), which 291 reduced basal area and substantially reduced regeneration density (Online Resource A3, e.g., Fig. A3.15). 292

![](_page_15_Figure_0.jpeg)

293

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).

295 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 296 area until the year 2150 (Fig. 3, top row). For BS, the previously broadleaf-dominated stand 297 298 experienced a complete transition to a Pinus silvestris-dominated woodland, which featured low basal area (< 15 m<sup>2</sup> ha<sup>-1</sup>) and was characterized by low densities of large trees (>30 cm 299 DBH), particularly under 'high browsing' conditions (Online Resource 3, Fig. A3.3 and Fig. 300 A3.5). In terms of species composition, all other sites showed increasing shares of broadleaved 301 trees (particularly Tilia for the site FW and Fagus at the other sites). Simulations including 302 303 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 304 305 (Fig. 3).

![](_page_16_Figure_0.jpeg)

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, 308 although the magnitudes of change differed between the two climate scenarios (Fig. 4, Online 309 Resource 2, Fig. A2.4-2.6). For the 'low impact' climate scenario, only slight decreases in basal 310 area resulted for the low-elevation sites (BS and FW), and higher basal area as well as rockfall 311 and avalanche protection for the high-elevation sites (Fig.4). These patterns were much more 312 pronounced for the 'high impact' scenario, where basal area and protection functions decreased 313 dramatically for the low-elevation sites. At the high-elevation sites, basal area as well as rockfall 314 and avalanche protection increased. In general, similar patterns emerged under either browsing 315 scenarios, although the magnitude of changes was higher in the 'high browsing pressure' 316 317 scenario, particularly for avalanche protection (Fig. 4 and Online Resource 2, Fig. A2.4-2.6).

![](_page_17_Figure_0.jpeg)

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.

319

# 320 *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 21<sup>st</sup> century, and to a smaller extent (Fig.5
and Online Resource 2, Table A2.1, Fig. A2.9).

![](_page_18_Figure_1.jpeg)

333

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.

336 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 337 stand basal area to <10 m<sup>2</sup> per ha (Fig. 6 and Online Resource 3, Fig. A3.26ff.). The reduction 338 339 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 340 Resource 3, Fig. A3.26 and Fig. A3.30). Furthermore, tree regeneration and growth benefited 341 more from the warmer conditions prevailing in 2080 compared to 2030, leading to a faster 342 recovery of basal area (Fig. 6). The recovery was however substantially impeded by high 343 browsing pressure (Fig. 6). 344

![](_page_19_Figure_2.jpeg)

345

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.

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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
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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 longterm recovery (Fig. 6 and Online Resource 2, Fig. A2.8).

![](_page_20_Figure_1.jpeg)

355

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).

#### 357 **DISCUSSION**

358 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 359 (≤1000 m a.s.l.), whereas higher elevation sites are more likely to benefit from warmer 360 conditions in the absence of disturbances. In contrast to the 'low impact' climate scenario, 361 abrupt negative impacts occurred for low-elevation sites under the 'high impact' scenario from 362 the mid-21<sup>st</sup> century onwards, leading to substantial shifts in species composition and stand 363 structure as well as a severe loss of protection function. Following our research questions, we 364 first discuss (1) the elevation-specific magnitude of change and (2) their temporal dynamics, 365 including the response to the exemplary disturbance scenarios. Ultimately, we discuss (3) the 366 limitations of this study and further capabilities of DVMs to provide decision support for forest 367 368 managers.

369

# 370 *Elevation-specific magnitude of change*

371 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 372 373 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 374 to moist, north-facing sites at high elevation. These contrasting conditions were reflected in the 375 differential climate change impacts, with detrimental effects predominating at the two low-376 377 elevation sites with southerly aspect (BS and FW). Empirical studies from dry inner-alpine 378 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, 379 Rigling et al. 2013) and decreased regeneration densities on low-elevation south-facing slopes 380 381 (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 382 383 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 384 climate conditions (see Online Resource 2, Fig.A2.9) and permit the growth of a mixed 385 deciduous forest with relatively high basal area in spite of the low soil water holding capacity 386 (ATRAGENE 1997). Nevertheless, our simulation results indicate that a number of severe 387 388 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 389 simulated sites within the forest enterprise. 390

391 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. 392 On the one hand, large-scale assessments provide important information on climate change 393 impacts (e.g., Bugmann et al. 2014, Bircher et al. 2015, SCNAT 2016), which may however 394 395 not be at a sufficiently detailed level for mountain forest enterprises located in topographically 396 complex and environmentally contrasting settings. As shown by the recent empirical study by 397 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 398 399 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 400 401 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 402 403 structure and composition at BS, the 'high impact' climate scenario induced drastic diebacks at 404 this site, despite the predominance of drought-tolerant species. In contrast, the higher elevation 405 site FW was less impacted despite the predominance of more drought-sensitive conifers. Our 406 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, SanchezSalguero et al. 2015, Etzold et al. 2019).

409 The simulated 'high impact' climate change effects at low elevations have pronounced 410 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 411 gravitational hazards. In the absence of a continuous forest cover, avalanche release risk is 412 substantially higher since the forest cover decreases snowpack depth (due to higher snow 413 interception), alters microclimatic conditions and increases surface roughness (Frehner et al. 414 2005). Similarly, rockfall risk increases drastically as stands formerly characterized by a large 415 416 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) 417 is expected to increase more than the importance of avalanches under climate change. Although 418 the seasonal time window with critical snowcover for avalanches is likely to decrease with 419 climate change, avalanche risks at lower elevations should not be underestimated, particularly 420 421 regarding snow-gliding on steep south-facing slopes (Bebi et al. 2016), e.g. at the site BS. In 422 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 423 424 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 21<sup>st</sup> 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 439 to increases in basal area and a shift in species composition towards more thermophilic 440 441 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 442 harvestable timber), simulated species composition showed a strong discrepancy compared to 443 the PNV simulations by the year 2150, indicating that the high fraction of Norway spruce (Picea 444 445 abies) remaining in the simulated stands is unlikely to represent a climatically suitable forest 446 composition (cf. Bugmann et al. 2014). Particularly under unmanaged conditions, stand 447 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 448 change likely leads to an increase in the risk of bark beetle outbreaks at higher elevations due 449 to an increase in the number of generations per year and prolonged annual flight periods 450 (Temperli et al. 2013, Bugmann et al. 2014). The advantages of increased growth may thus be 451 counteracted by negative impacts of enhanced biotic or abiotic disturbances, as shown in our 452 exemplary disturbance simulations. Including forest management in our simulations however 453 454 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. 455

With respect to species responses to climate change along the elevation gradient, our simulation 456 457 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 458 contemporary climate change that are reporting an upward expansion of the distribution ranges 459 of trees (e.g., Penuelas and Boada 2003, Vitasse et al. 2012), although species-specific 460 responses can be complex and site-specific (e.g., Gazda et al. 2019). Furthermore, 461 462 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. 463 2016), and suggest an increase in the abundance of Fagus sylvatica at high elevations under 464 465 future climate change (Schwörer et al. 2014). The projected shifts of dominant species are thus 466 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 467 468 at high-elevation managed sites) may be overestimated (cf., e.g., Wohlgemuth and Moser 2018). 469

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# 471 *Temporal patterns of change*

472 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 473 of temperature changes show relatively small differences between the emission scenarios in the 474 first half of the 21<sup>st</sup> century, they differ substantially until the end of the century for Switzerland 475 (CH2011). A similar trend was evident from the simulated forest properties, with little change 476 477 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 478 to be gradual for the 'low impact' scenario, but more abrupt for the 'high impact' scenario at 479 sites  $\leq 1000$  m a.s.l. While the specific time points of these drastic changes are subject to 480

considerable uncertainty, several studies suggest a much higher probability and frequency of 481 482 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 483 sudden drought-related tree mortality (Allen et al. 2015). The risk of this sudden dieback is 484 485 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 486 these findings, our results suggest that a 'high impact' climate change scenario leads to a much 487 higher risk of rapid drought-related forest dieback for the late 21<sup>st</sup> century. 488

If the current trend of failing to meet the targets of the Paris agreement continues (UNEP 2019), 489 low- to mid-elevation mountain forests may be at particular risk of drought-related tree 490 mortality and substantial losses in their protective function against gravitational hazards. To 491 avoid or at least mitigate this situation, forest management should particularly promote the 492 regeneration with climate-adapted species (SCNAT 2016). Our results demonstrate how a 493 DVM approach can provide decision support in the selection of potentially suitable species and 494 help to estimate the timespan remaining for forest management to address these issues before 495 496 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 497 forest planning (Streit et al. 2017). Based on the results from BS, considerable impacts of 498 climate change are likely to be expected in our case-study enterprise from around the mid-21<sup>st</sup> 499 500 century under a 'high impact' climate scenario, suggesting that forest management has less than 501 three decades to establish sufficient advance regeneration, which is a critically short time window in mountain forests (Ott et al. 1997). 502

503 Besides the direct impacts of climate change on low elevation sites, abiotic and biotic 504 disturbances by windthrow and bark-beetle attacks pose a threat to the spruce forests at higher 505 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 506 pressure also plays a key role for post-disturbance recovery in high elevation forests. Notably, 507 508 a higher post-disturbance basal area and a faster recovery was simulated when the disturbance (windthrow or bark beetle) occurred in the late 21<sup>st</sup> century (year 2080), which was due to a 509 higher abundance of advance regeneration induced by management and the additional effect of 510 the warmer climate. These findings are supported by empirical studies, e.g. by Schwitter et al. 511 512 (2015), who evaluated 24 years of forest dynamics at windthrow sites in Switzerland and found 513 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 514 515 importance for the protection function of a forest, since trees of a certain minimum height are 516 required to provide protection against avalanches and rockfall (Noack et al. 2004). Furthermore, 517 browsing pressure is a key factor that can reduce establishment and slow down post-disturbance 518 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). 519 It has to be noted, however, that rather than providing a realistic projection of future forest 520 dynamics under changing disturbance regimes, our exemplary disturbance simulations only 521 522 aimed to test the broad effects of timing of disturbance, previous management and browsing 523 pressure on recovery. Despite these limitations, our results demonstrate at a general level that 524 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 525 526 forests.

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### 528 Using DVMs as decision support tools for mountain forest managers

529 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).

536 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 537 (LiDAR), as shown by Maroschek et al. (2015). Rather than using the spatially limited approach 538 of representative stands, as in our study, some DVMs are capable of representing the spatial 539 540 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 541 of landscape models furthermore allows to simulate exogenous disturbances as self-emergent 542 properties of the system (e.g., Seidl et al. 2014, Temperli et al. 2015), which was not possible 543 544 in our stand-scale DVM. However, the increasing degree of spatial detail comes with its own 545 challenges, e.g. a strongly increasing data demand (see also review by Keane et al. 2015), which 546 reduces the likelihood of such models being used in the absence of a dedicated and specifically funded research project. 547

Another aspect that was not investigated in detail in this study is the use of DVMs to explore 548 alternative forest management approaches to optimize the provisioning of multiple goods and 549 services. The capacity of DVMs to assess trade-offs and synergies between multiple ecosystem 550 services has been addressed more recently, e.g. by studies in different mountain areas within 551 Europe by Mina et al. (2017a) and Langner et al. (2017). An overview of the management 552 553 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. 554 2017b). Ultimately, multi-criteria decision analyses can be used in combination with DVM 555

simulations to facilitate the identification of appropriate management alternatives for a widerange of forest goods and services (e.g., Wolfslehner and Seidl 2010).

558 Overall, DVMs are increasingly suitable tools for providing decision support in mountain 559 forests. A broader coverage of studies from different mountain regions would thus be highly 560 valuable from a forest management perspective as well as from a scientific perspective, e.g. for 561 synthesizing overarching conclusions on the impact of climate change in mountain regions 562 (e.g., Price et al. 2011).

563

#### 564 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 571 forest vulnerability, assessments of the timing and magnitude of change, quantification of 572 573 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 574 575 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 576 577 receive particular attention. (2) Forest management was of high importance to induce sufficient 578 advance regeneration, which is key to ensure forest resilience and specifically the protective 579 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.

585 Ultimately, the results from this study emphasize that international efforts to reach the goals of 586 the Paris Agreement are of crucial importance for mountain forests, as unabated climate change 587 is likely to severely deteriorate forest health as well as the services that are provided by these 588 forests.

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# 590 ELECTRONIC SUPPLEMENTARY MATERIALS:

- 591 ESM\_1: Extended material and methods
- 592 ESM\_2: Additional simulation results
- 593 ESM\_3: Detailed site-specific projections

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