8 — Climate change impacts on tree species, forest properties, and ecosystem services

○
● tree species
● forest properties
● ecosystem services
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– Swiss forests experience strong impacts under the CH2011 scenarios, partly even for the low greenhouse gas scenario RCP3PD. Negative impacts prevail in low-elevation forests, whereas mostly positive impacts are expected in high-elevation forests.

– Major changes in the distribution of the two most important tree species, Norway spruce and European beech, are expected. Growth conditions for spruce improve in a broad range of scenarios at presently cool high-elevation sites with plentiful precipitation, but in the case of strong warming (A1B and A2) spruce and beech are at risk in large parts of the Swiss Plateau.

– High elevation forests that are temperature-limited will show little change in species composition but an increase in biomass. In contrast, forests at low elevations in warm-dry inner-Alpine valleys are sensitive to even moderate warming and may no longer sustain current biomass and species.

– Timber production potential, carbon storage, and protection from avalanches and rockfall react differently to climate change, with an overall tendency to deteriorate at low elevations, and improve at high elevations.

– Climate change will affect forests also indirectly, e.g., by increasing the risk of infestation by spruce bark beetles, which will profit from an extended flight period and will produce more generations per year.

8.1. INTRODUCTION

Climate is a key factor shaping the forest environment; thus changes in the climate are likely to strongly affect forest ecosystems by altering the physiology, growth, mortality and reproduction of trees, the interactions between trees and pathogens, and ultimately the disturbance regimes (winds, wildfires, insect attacks, etc.). The sensitivity to such changes depends on the level that is considered (landscapes vs. forest, stands vs. single trees) and on the specific site conditions (e.g., Elkin et al., 2013, Büntgen et al., 2008, Babst et al., 2013). These complex influences indicate that a changing climate may lead to non-linear responses, tipping points, etc., particularly since the longevity of trees implies that many individuals present today will experience substantial changes of the climate before they will be replaced by the next generation. Thus, the question arises to what degree current trees and forest ecosystems are able to cope with a changing climate.

Here, a selection of studies of economically relevant and regionally typical impacts is presented, based on the materials that were available at the time of writing this report.

An empirical study on the relation between climate conditions and growth of Norway spruce *(Picea abies)*, the most widespread and economically important tree species in Switzerland (Cioldi et al., 2010), is used to outline impacts at the level of individual trees. Then, a suite of modeling studies addresses issues that are not amenable to direct observation or experimentation. At the scale of the entire country, changes in the potential distribution of widespread tree species, focusing

‹ Growth conditions for widespread and economically important tree species in Switzerland may deteriorate with warming on the Swiss Plateau („plenter" forest at Sumiswald, Emmental on October 23, 2012; photo: FOEN).

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on Norway spruce and beech *(Fagus sylvatica)*, are investigated, combining results from static distribution models and a dynamic simulation model. At the landscape level, species-specific biomass changes are projected in two case studies for sites on the Swiss Plateau and in the canton of Ticino. Forest properties and three key ecosystem services (timber production, carbon storage, and protection from snow avalanches and rockfall) are assessed along elevational gradients in two Alpine catchments. Finally, the effect of future climate change on the spruce bark beetle *(Ips typographus)*, a major cause of mortality in spruce forests, is assessed, again at the national scale (Wermelinger, 2004; Meier et al., 2009).

8.2. METHODS

The SEASONAL-REGIONAL and DAILY-REGIONAL datasets from CH2011 (Chapter 3) are used in this study, including two non-intervention scenarios (A1B and A2) and one mitigation scenario assuming low emissions (RCP3PD). These data are augmented by raw ENSEMBLES simulation data for A1B (Chapter 3).

The potential impact of climate change on **growth of Norway spruce** is investigated using an empirically derived relationship between radial stem increment and mean temperature and precipitation sum over the growing season (April to September). The analysis is based on a sample of 156 trees from 11 sites in Switzerland and in the Aosta valley. Potential climate change impacts are discussed for two sites sampling the biogeographic diversity of Switzerland: Biel, representing the relatively wet-warm Swiss Plateau, and Goppenstein, located in a cool-dry inner-Alpine valley. Both sites are within the CHW domain of the CH2011 scenarios.

Climatic suitability maps for spruce and beech are generated using six statistical species distribution models (Guisan and Zimmermann, 2000) for each species, based on forest inventory data from >80'000 plots from the entire European Alps and nearby lowlands. Future projections are based directly on A1B climate simulations from six of the ENSEMBLES model chains that underlie the CH2011 scenarios (Chapter 3), which are downscaled to 1 km raster size. Climatic suitability for A1B is then projected for all 36

combinations of climate and statistical models, and ensemble maps are created showing to what degree the models agree on projected species presence/absence. These suitability maps represent the climatic potential of a tree species to establish and regenerate under the projected climate, but they do not indicate how fast changes will occur. This static approach is combined with simulation results from the TreeMig model to quantify the importance of migration lags. TreeMig is run with one A1B simulation from ENSEMBLES, downscaled to resolution of 200 m × 200 m. TreeMig incorporates forest dynamics and a mechanistic description of tree migration for 30 species (Lischke et al., 2006). Forests are restricted to the current forest area until 2007, and allowed to expand into alpine meadows at later times.

Forest dynamics at the site and catchment scale are simulated with the mechanistic models ForClim (Rasche et al., 2012) and LandClim (Elkin et al., 2012). ForClim is a detailed model of stand-scale forest succession whose main aim is to achieve appropriate sensitivity to climate and high local accuracy. LandClim incorporates a simplified version of ForClim and adds large-scale disturbances such as windthrow, wildfires, and bark beetle infestations.
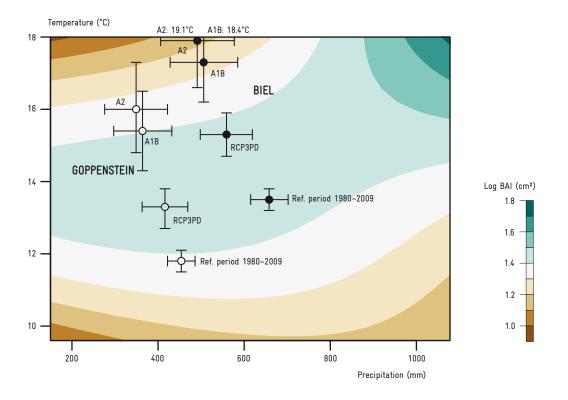
LandClim is applied to two ~3000 ha landscapes surrounding two low-elevation lakes, Lobsigensee (514 m asl), Canton Bern, and Lago di Origlio (419 m asl), Canton Ticino. The model is initialized by simulating current forests based on recent local climate observations, and run through 2011–2300 using the CHW and CHS regional projections of CH2011 (2011). Climate scenario data are interpolated linearly between the CH2011 periods, and extended at constant values from 2100 through 2300. At Lobsigensee, a management regime to favor spruce is simulated throughout the simulation period. At Lago di Origlio, chestnut *(Castanea sativa)* cultivation is simulated until 1950, followed by abandonment to mimic past and current land use practices.

Using LandClim and ForClim, climate change impacts on forests and related **ecosystem services** are simulated in the two climatically distinct mountain valleys Saas (Canton Valais) and Dischma (Canton Graubünden; Elkin et al., 2013). This allows for a comparison of how the impacts on ecosystem services vary between

and within regions. The simulated forest management incorporates the current region-specific practices that are aimed primarily at maintaining (1) the protective function of forests against avalanches and rockfall, and (2) structural diversity. The models are initialized with current climate and management regime, and run transiently for 2011–2300 for all three climate scenarios (RCP3PD, A1B, and A2) as described above. Changes in the central Alpine climate are approximated as the average of the CHW and CHE scenarios of CH2011 (2011).

To estimate the impact of climate change on the infestation potential of **bark beetles**, the number of annual generations is used as a key indicator variable. Since each generation attacks new trees and propagates further from there, this is a good measure of the overall infestation risk. A population dynamics model is used that covers the basic processes of bark beetle phenology, i.e., development from egg to adult, maturation feeding, swarming, oviposition, and sister breeding (Annila, 1969). Beetle generations are projected for each scenario period (2035, 2060, and 2085) using the DAILY-LOCAL dataset for the A1B greenhouse gas scenario, which represents ten model chains from ENSEMBLES (Chapter 3). The ten resulting projections of beetle generation numbers are then averaged. In the current model version, beetle population dynamics are driven by climate, but independent of the current distribution of spruce trees, their susceptibility, and resistance to bark beetle attack.

8.3. RESULTS

The statistical model shows that **Norway spruce growth** is strongly reduced if mean temperatures exceed 15°C and precipitation falls below 600 mm during the growing season (Figure 8.1). Temperatures below ca. 13°C also limit spruce growth, but sensitivity to

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Figure 8.1: Natural logarithm of basal area increment (BAI; i.e., the annual change in the cross-sectional area of the stem) of spruce in the reference period and for the period 2085 as a function of average temperature and precipitation sum during the growing season (April–September) for the RCP3PD, A1B, and A2 climate scenarios for the sites Goppenstein (cool dry; open circles) and Biel (warm-wet; filled circles). The plot is based on the best linear mixed-effects model. Error bars show the 95% confidence interval for the reference period, and the uncertainty range between upper and lower estimates for the CH2011 climate scenarios.
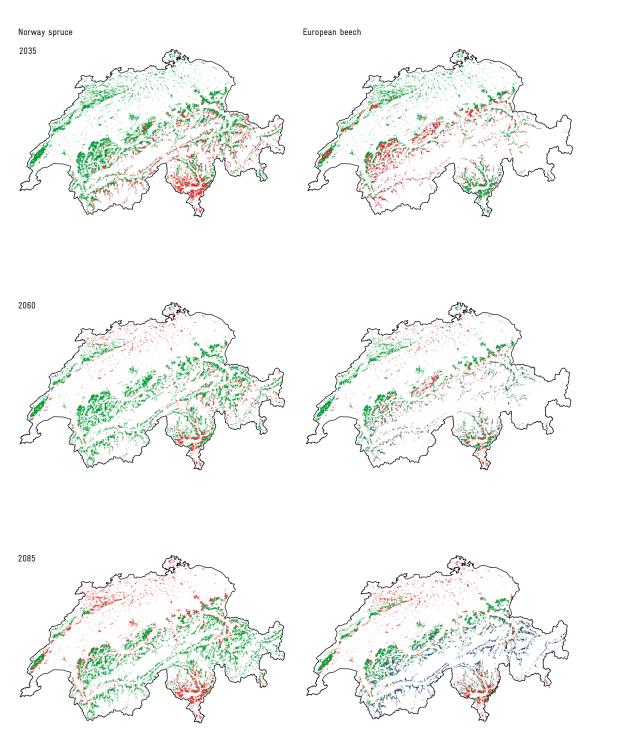
precipitation is low under these conditions. The CH2011 scenarios depict summer warming (up to 6°C until 2085) and drying (up to 40% precipitation reduction) across Switzerland. Impact on spruce growth will vary depending on the present climate conditions at the respective sites. Moderate warming, such as in RCP3PD, stimulates growth at cooler sites (Goppenstein) or has little effect where precipitation is sufficient (Biel). However, as water demand increases with temperature, severe drought will reduce growth at already warm and precipitation-limited sites such as the central Valais. Drought will also occur widely when warming is very strong, as in the A1B or A2 scenarios at later scenario periods (2.7 to 4.8°C average warming during the growing season until 2085), except at presently cooler sites with ample precipitation, where growth is likely to be enhanced (Figure 8.1). As these considerations are based on average changes of climate variables, they do not take into account potential changes in climate variability (Chapters 2 and 3).

Climatic suitability projections are broadly in agreement with these results. Species distribution models (SDMs) project the Swiss Plateau to become unsuitable for spruce by the year 2100 in the A1B scenario (Figure 8.2). However, sizeable areas are classified as unsuitable already in the near future, in contrast to the empirical growth projections (e.g., for the Swiss Plateau where Biel is located; Figure 8.1). The dynamic model TreeMig projects spruce to persist on the Swiss Plateau throughout the century, though at declining levels. Some disagreement between the static SDM approach and the dynamic TreeMig simulations is expected, as the latter simulates transition between forest types, whereas the former yields equilibrium distributions only. However, the discrepancy between model results points to considerable uncertainty about spruce viability on the Swiss Plateau. High elevations exhibit both improving suitability and increasing prevalence of spruce in both the SDM and the TreeMig simulations, indicating that spruce distribution will not be limited by migration.

For beech, a similar shift of suitable climate away from the Swiss Plateau and toward higher elevations is projected (Figure 8.2). Again, the results disagree for the Swiss Plateau, with TreeMig simulating beech as present throughout the A1B scenario. However, the TreeMig simulations suggest that beech, in contrast to spruce, does not invade the high elevations by 2100 due to slow migration.

In general, migration speed is limiting colonization by trees at the rising treeline, thus leading to a deferred build-up of forest biomass in these areas. However, migration does not noticeably affect country-wide forest biomass. Downy oak *(Quercus pubescens)*, a species currently rare in Switzerland, is simulated to migrate only slowly. This suggests migration limitations where large distances have to be overcome. Mediterranean, drought–adapted species could experience a similar limitation and may have difficulties to reach by natural migration the dry regions of the Swiss Plateau and Alpine valleys, which expand rapidly under the A1B and A2 scenarios.
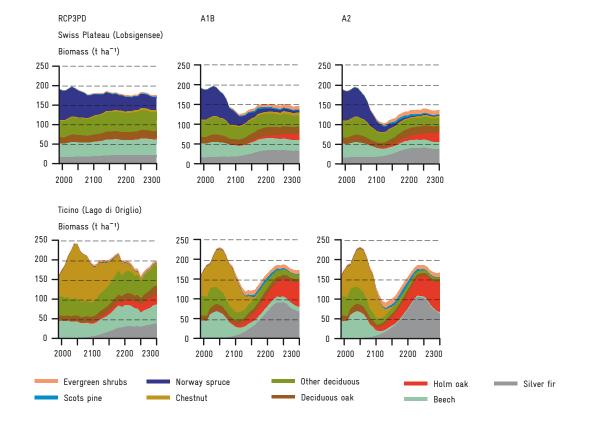
Regarding **forest dynamics** in small landscapes at Lobsigensee and Lago di Origlio, the RCP3PD scenario leads to rather small and gradual changes of forest biomass and species composition, whereas major changes are evident after the year 2050 under the scenarios A1B and A2 (Figure 8.3). These changes are driven by a scenario-specific increase in drought that causes a decline of spruce in all scenarios at Lobsigensee. Despite being favored by forest management, spruce largely disappears by 2100 in the A1B and A2 scenarios. At Lago di Origlio, chestnut declines due to drought under all scenarios, especially under A1B and A2. At both sites, after an initial increase of simulated landscape-scale tree biomass, strong declines are expected under all scenarios (in particular A1B and A2), with a minimum around 2100. The simulations suggest that silver fir *(Abies alba)* would increasingly prosper at both sites, as this evergreen species is favored over its deciduous competitors by the longer growing season, and over spruce by its greater drought tolerance. This is consistent with pollen records from Southern Switzerland showing long phases of fir dominance prior to agricultural land use and before anthropogenic fires became important (ca. 10 000–5 000 years ago; Tinner et al., 2005). However, fir is quite sensitive to wildfires, and its saplings are a preferred diet of roe and red deer. The latter currently occur in higher population densities than assumed in the simulations and could thus prohibit fir from reaching its simulated potential. Alternatively, the

Norway spruce

European beech

2035

2060

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2085

Figure 8.2: Comparison of the future suitability of tree species (left: Norway spruce; right: European beech) as simulated by empirical species distribution models (SDMs) and a model with mechanistic migration and dynamics (TreeMig). Red areas are projected to be unsuitable for the species by the SDMs, whereas in TreeMig simulations they still persist; blue areas are suitable according to SDMs, but not invaded by the respective species in the TreeMig simulations. Green areas indicate agreement between the two model approaches.
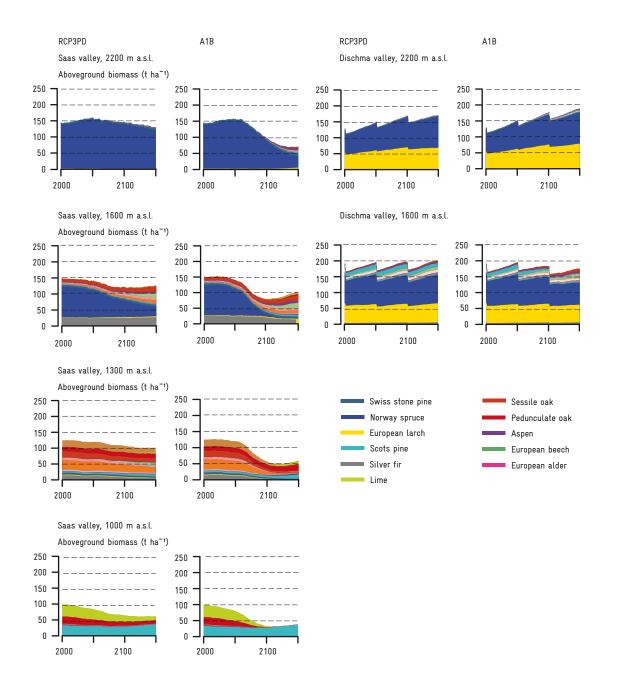
results suggest the continuing relevance of drought tolerant deciduous species (e.g., deciduous oaks) and an increased future potential for holm oak *(Quercus ilex)*, an evergreen Mediterranean species that is more fire-tolerant and grows well on dry sites even under the A2 scenario (Figure 8.3). However, this species is limited in its natural migration due to the large distances involved and migration barriers that would have to be overcome.

In terrain with large elevational gradients such as the Dischma and Saas valleys, simulation results indicate a fine-grained response to climate change both within and between regions. In the Saas valley (Figure 8.4), the lowest and driest elevations are most prone to increasing drought. Even the limited climate changes of the RCP3PD scenario lead to a strong decrease of biomass there. At mid-elevations, species composition is affected, but biomass decreases are small, and at the highest elevations an increase of biomass is

simulated until 2050, followed by a slight decline back to the initial values. By contrast, the A1B scenario results in a strong biomass decrease in the long term at all elevations, also inducing a change of species composition. Drought gradients are very steep in the landscape, and it is quite difficult to precisely simulate species limits along such gradients. Thus, species such as lime *(Tilia cordata)* are incorrectly simulated to thrive at lower elevations in the Saas valley under the current climate. However, this does not affect the conclusion regarding the direction and magnitude of future changes in total forest biomass or tree species diversity. In contrast to the lowland sites (Figure 8.3) and the dry Saas valley (Figure 8.4), the cool-wet Dischma valley will not experience marked drought. Both the RCP3PD and the A1B scenario imply little change in the lower parts of the valley around 1600 m asl, and a biomass increase at high elevations near current treeline, i.e., around 2200 m asl (Figure 8.4).
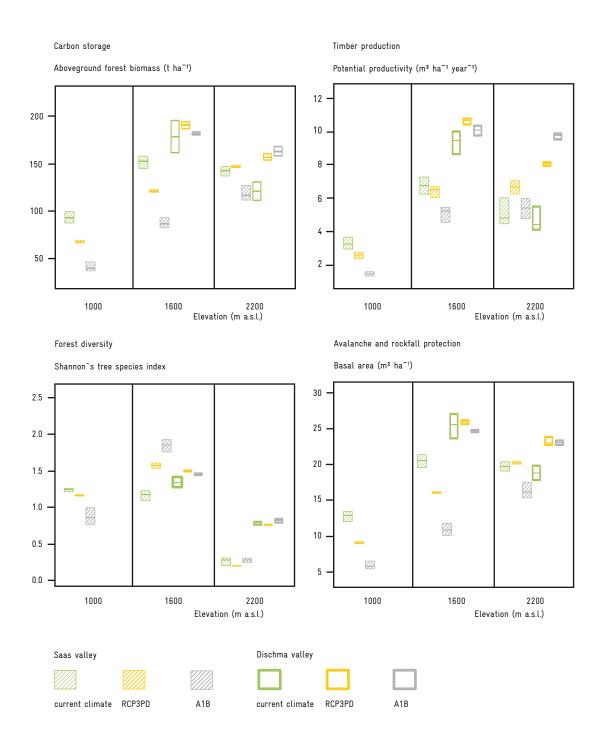
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Figure 8.3: Vegetation simulated with the LandClim model within 3 km of Lobsigensee, Canton Bern (top row) and Lago di Origlio, Canton Ticino (bottom row) under the RCP3PD (left), A1B (middle), and A2 (right) climate scenarios. Average species–specific biomass for the entire simulated landscapes is shown.

Future trends in the portfolio of three **ecosystem services** (ES; Figure 8.5) are diverse and partly follow the trends in forest properties (Figure 8.4). Large negative impacts are projected for low and intermediate elevations in initially warm-dry climates (lower part of the Saas valley), where even the RCP3PD scenario results in negative drought-related impacts particularly regarding forest diversity and protection from avalanches and rockfall. In contrast, at higher elevations, and in regions that are initially cool-wet (Dischma valley), forest ES are simulated to be comparatively resistant to climate change. At mid-elevations, variability of ES across regions will be highest, and most ES will be affected negatively. These results indicate that the vulnerability of forest ES to climate change will vary
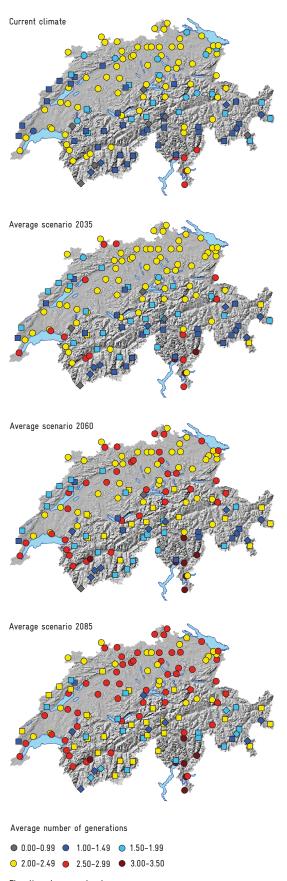
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Figure 8.4: Forest biomass and species composition in the Saas (left) and Dischma (right) valleys under the RCP3PD and A1B climate scenarios as simulated by the ForClim model. Rows refer to different elevations. The stair-like pattern for the Dischma valley results from the fact that one specific stand is simulated, where the management interventions take place every 50 years.

Carbon storage

Aboveground forest biomass (t ha⁻¹)

Timber production

Potential productivity (m³ ha⁻¹ year⁻¹)

Forest diversity

Shannon`s tree species index

Avalanche and rockfall protection

Basal area (m² ha⁻¹)

Saas valley

current climate   RCP3PD   A1B

Dischma valley

current climate   RCP3PD   A1B

Figure 8.5: Projected impact of climate change on four forest ecosystem services (ES) at three elevations in the Saas and Dischma valleys based on the ForClim and LandClim models. The projected range and median of ES under current climate conditions, moderate climate change (RCP3PD) and more extreme change (A1B) are shown for the time period centered around the year 2085. The ranges shown in the figure refer to stochastic variability inherent in the ecological processes, not model uncertainty.

Current climate

Average scenario 2035

Average scenario 2060

Average scenario 2085

Average number of generations

- ● 0.00–0.99 ● 1.00–1.49 ● 1.50–1.99
- ● 2.00–2.49 ● 2.50–2.99 ● 3.00–3.50

Elevation above sea level

○ < 1000 m   □ 1000–1800 m   ◇ > 1800 m

considerably, with some services such as protection against avalanches and rockfall being sensitive already to moderate climate change, but other services such as carbon storage being reasonably resistant. Thus, a heterogeneous response of mountain forest ES to climate change is to be expected both between and within regions. These results do not, however, consider the likely increased activity of bark beetles and other pests and pathogens, which may modify the ecosystem response rather strongly, as outlined below.

Bark beetles will most likely benefit from a warmer and potentially drier climate. Almost all over Switzerland, beetle populations will produce a higher average number of generations per year (Figure 8.6) and profit from a prolonged annual flight period. Spring swarming of overwintering generations and summer swarming will occur earlier (on average four and three weeks, respectively, under the A1B scenario in 2085). Particularly on the Swiss Plateau, and in some Alpine valleys with a current maximum of two beetle generations, a third generation will become frequent by 2085 (Figure 8.6). In the Alps and the Jura Mountains, generation numbers will increase from between one and two at present, to regularly two. Moreover, earlier spring swarming will generally be more pronounced at higher elevations in the Alps and the Jura Mountains than on the Swiss Plateau. The increased pressure of bark beetles (Figure 8.6) on spruce needs to be interpreted in the context of the limited drought tolerance of that species: drought periods may increasingly lead to growth reductions (Figure 8.1), increased susceptibility to bark beetle attacks and thus higher mortality.

8.4. IMPLICATIONS

Drought impacts on forests are already evident in the driest parts of Switzerland, e.g., at low elevations in the Valais (Rigling et al., 2012; 2013). These impacts are reinforced by biotic influences, but depend also on land use

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Figure 8.6: Average potential number of spruce bark beetle generations per year at 141 locations in Switzerland for the reference period 1980–2009 and under the A1B climate scenario for 2035, 2060, and 2085, respectively.

changes (Dobbertin et al., 2007). Another example of a complex climate change impact is the ongoing spruce decline on the Swiss Plateau, which is triggered by natural disturbances, i.e., storms and subsequent bark beetle infestations, and promoted by summer droughts (Engesser et al., 2008; Temperli et al., 2013). Many other indirect effects of climate change influence forest ecosystems, e.g., the spread of novel pathogens and pests introduced through global trade. Thus, climate impacts on forests will always be the result of multiple factors, whereas the scenario calculations of the present chapter tend to focus on few factors only. Accordingly, while the simulation results should be useful for guiding management decisions, they must not be taken literally as 'prognoses' of future forest states.

The results in this chapter are broadly in line with the large-scale impacts of climate change that were outlined in the Fourth Assessment Report of the IPCC (IPCC, 2007b), and provide a richer picture of the implications of climate change for forests at the national to local scale. They are also in agreement with the findings from the earlier report CH2050 (OcCC 2007), which provided a qualitative assessment of climate impacts. The results for the mitigation scenario RCP3PD represent an advancement with respect to the aforementioned reports. While for many forest ecosystem services the climate of this scenario would be "safe", for some it is clearly not. This finding shows the very high sensitivity to climate change of some Swiss forests.

The impacts of future climate on forest properties will strongly differ between sites. While it is evident that climate scenarios with larger changes in temperature and precipitation will affect forests more strongly, forest vulnerability also depends on current site conditions and current stand properties. Empirical evidence (Figure 8.1) and simulation studies (Figures 8.2–6) suggest greatest changes for sites where forest growth is currently limited by water availability or low temperature, i.e., at the lowest and highest elevations of the current forest distribution in Switzerland.

At dry sites, e.g., low elevations of inner-Alpine valleys, already small changes of the climate (i.e., the RCP3PD scenario) can trigger major changes in biomass, forest composition, and the provision of ecosystem services.

There, active management measures to alleviate drought (such as thinning) or even changes to novel tree species compositions may be sought.

In contrast, water availability is usually not limiting at cool sites in the Swiss Alps, which will therefore become increasingly suitable for forest growth and forest expansion. This will accelerate the trend of increasing forest area at high elevations, which may or may not be welcome, depending on the ecosystem service considered (e.g., landscape aesthetics vs. carbon storage).

At intermediate sites, the uncertainty about future biomass and forest composition is considerable, and current impact models often disagree. An example is the future presence of spruce on the Swiss Plateau. In such environments, different trajectories are possible, and may be largely determined by climate extremes, which are exceedingly difficult to project in timing, frequency and severity. A robust strategy under these conditions would be to diversify the portfolio of tree species where this is feasible with limited efforts, so as to allow for many different future trajectories of forest dynamics.

The case studies suggest a reduction in the provision of ecosystem services at low elevations in dry inner-Alpine regions and an increase at high elevations. The potential for conifer timber production and carbon sequestration will shift from the Swiss Plateau to the Alps and Jura Mountains. However, timber harvesting is more difficult and expensive in these regions, and the risk of bark beetle attacks on spruce also increases in a warmer climate. Protection forests will be particularly threatened at low elevations of inner-Alpine valleys, but may profit from climate change at higher elevations. Overall, this means that, from a forest sector perspective, negative changes in the dry Inner Alps will likely be contrasted by neutral to positive changes in the wetter parts of the Alps and in the Jura Mountains.