



# Forest adaptation to climate change—is non-management an option?

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## Abstract

• **Key message** Climate change is posing a considerable challenge to foresters. The intensity of required adaptive measures and the relevance of old-growth forests as benchmark for managed forests are debated. Forest managers need to make decisions on stand treatment that are based on climatological and biological parameters with high uncertainties. We provided the conceptual basis for adaptive forest management and provide a number of case studies that reflect the options and limitations of ways of coping with climate change. The examples are derived from the experience of the authors. We conclude that only few forest types are either not strongly affected by climate change or do not require immediate adaptations of forest management. Many productive forests have stand properties that are decisively shaped by past management decisions, such as tree species composition, age distribution, rotation period, and stand structure. Maintaining these properties under the influence of climate change requires continuous and even increasing efforts of forest managers.

**Keywords** Adaptive forest management · Old-growth forest · Managed forest

## 1 Introduction

### 1.1 Impact of climate change on forests

Climate change as a combination of warming, changing precipitation, an altered pattern of extreme events, and a changing disturbance regime affects forests fundamentally. The risk of adverse effects of climate change is increasing as the warming trend is continuing (Steffen et al. 2015). Forests respond to climate change in various ways driven by the local site

conditions and the adaptive potential of trees. Climate change may also trigger successional processes which lead to changing plant communities (Bolte et al. 2014). At a certain point, the provision of ecosystem services from forests, such as timber production, protection against natural hazards, water provision, and biodiversity, may be critically diminished.

Changes in climate conditions can affect disturbance regimes of forest ecosystems (Seidl et al. 2017). Disturbances are a natural element of ecosystem development and can reset the possible pathways of change at irregular intervals. Abiotic

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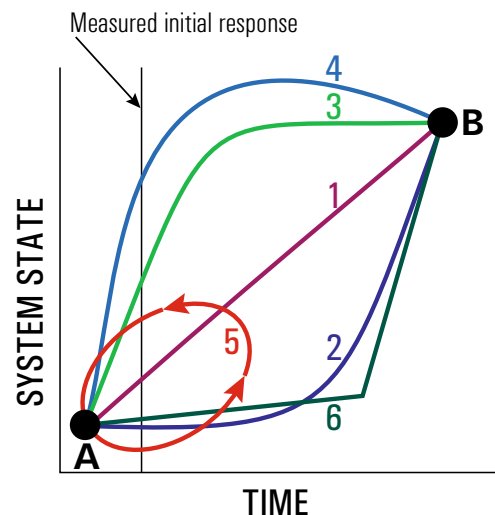
disturbances such as the size and frequency of wildfires and storm events have been linked to climate change, even though the immediate causal relationships are not yet proven (Allen et al. 2010; Gardiner et al. 2010). Clearer is the relationship between climate change and biotic disturbances. As biological processes are temperature controlled, pests and pathogens are expected to change their habitat ranges and are becoming virulent in areas where they have not reached critical population densities earlier (Battisti et al. 2005; Marini et al. 2012; Netherer and Schopf 2010). There is strong evidence that some recent outbreaks of bark beetles and defoliating insects are related to climate change, and these are having large impacts on ecosystems as well as on communities of forest insects (Kurz et al. 2008; Pureswaran et al. 2018).

### 1.2 Climate change, future site conditions, and possible responses of forests

Global change alters site properties such as climate, water supply, and the nutrient supply from soils. For the close linkage between site conditions and forest development, the term ‘iron law of the site’ has been coined, emphasizing that trees cannot outgrow the limits imposed by soil properties and regional climate (Hildebrand et al. 1996). Climate change can alter tree species ranges and forest communities to species mixtures that are unfamiliar and unprecedented (O’Hara 2016). Information on historical tree species compositions is therefore often of little value for devising measures of adaptive forest management. Hickler et al. (2012a) have shown that climatic change is affecting the potential natural vegetation to a large extent. The change can happen within a few decades at regional hotspots and slower at other places.

Several tools are available to assess future site conditions based on externally defined climate scenarios (Rogelj et al. 2012; IPCC 2013). Niche modeling has been used to approximate the future spatial distribution of tree species and to indicate the expected habitat change (Hanewinkel et al. 2012; Schelhaas et al. 2015; Wang et al. 2016; Zimmermann et al. 2009). Niche models use predicted site conditions at different time slices as input parameters and are yielding the dominant tree species that are most suitable under the respective site conditions. In succession models, other than in niche models, the competition of trees and the velocity of tree migration are considered (Bircher 2015; Hülsmann et al. 2018). The models accommodate forest management decisions. Both types of models have strengths and known shortcomings.

The trajectories from the current state of forests to a future state are uncertain. Direct evidence from climate manipulation experiments is sparse and allows for different interpretations. After a rather short observation period of climate manipulation experiments, several pathways of forest development are possible (Fig. 1). Forests can either develop in linear fashion from status A to B (pathway 1 in Fig. 1). Such a system



**Fig. 1** Different temporal patterns of ecosystem responses to climate change. Pathway 1: linear response; 2: response with lag effect; 3: acclimatization; 4: overshoot; 5: homeostasis; 6: tipping point (after Rustad 2006)

reaction would call for slight and stepwise adaptations of the management system. Forests could also respond to a changing environment with some delay (pathway 2, ‘lag’, in Fig. 1) and would later respond strongly with a swift system state. Forests could change strongly in the early phase of a change and later acclimatize to the new conditions (pathway 3, ‘acclimatization’ in Fig. 1), or even initially overshoot (pathway 4, ‘resource limitation’). Another case is ‘homeostasis’ where the system is particularly stable and does not change its state at all (pathway 5 in Fig. 1). Finally, the system could tolerate initial changes and have a sudden system change after passing a critical threshold (pathway 6 in Fig. 1).

### 1.3 Need for adaptation and fundamental adaptation strategies

The change in site properties such as temperature, water, and nutrient supply due to climate change and the need for adaptive management of forests is widely agreed among scientists and practitioners. The large uncertainty of predicted future conditions, additively driven by the wide range of regionally valid climate scenarios, and the uncertainty of the response of forests according to Fig. 1 are impediments for the implementation of effective adaptation measures. However, the uncertainty of predicted site conditions is not the consequence of knowledge gaps but rather represents the natural variability of the development of long-living forests under changing site conditions. The results of ongoing research on adaptive forest management will increase system understanding, but will not alleviate the wide system-inherent variability. Forest practitioners will therefore make decisions based on incomplete information. Some of the suggested forms of adaptive forest management are rather generic. Increases in tree species diversity and structural diversity are

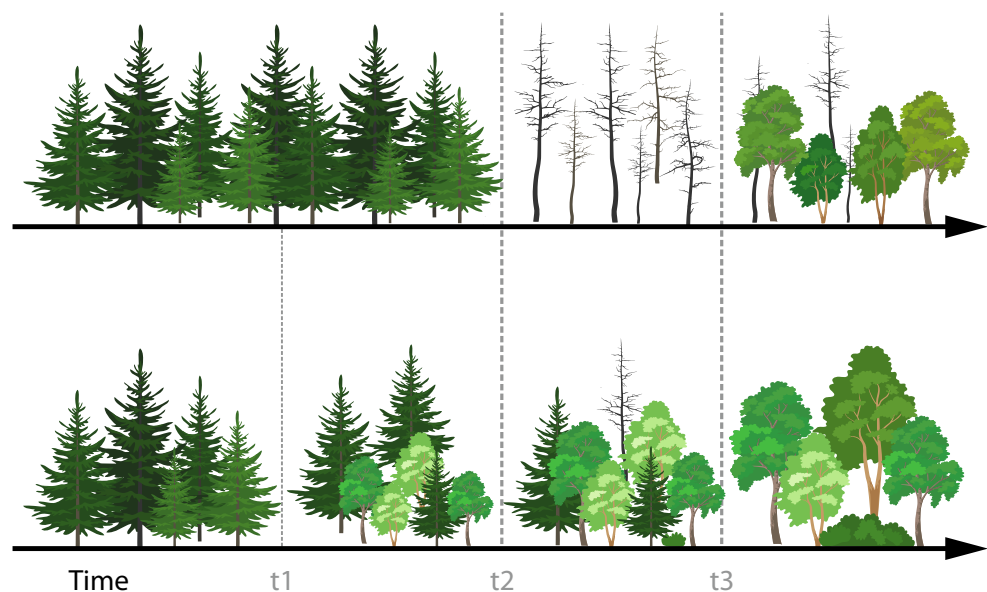
distributing risks within a forest stand and are standard recommendations to increase ecosystem stability. Other recommendations such as replacing highly productive yet vulnerable tree species with trees that are more tolerant to future climate conditions are safe, yet they imply undesired economic consequences for the forest sector (Brang et al. 2014). The implementation of adaptive forest management concepts will change traditional forestry. Monitoring activities in order to early detect infestations of pests and pathogens need to be intensified, additional tree species combinations need to be investigated, and the production cycle of forests will often be shorter than presently. At sites with emerging drought periods, the most suitable time for planting tree seedlings needs to be shifted. Changes in forest management will alter the supply of different timber types and assortments. This will affect the entire wood processing sector.

Non-management or passive adaptation of forest management is using the natural, inherent resilience, and succession processes of forest ecosystems and implies a reduction or even cessation of silvicultural input. The assumption is that natural ecosystem dynamics will exert a dynamic self-regulation of the ecosystem in the face of climate change. This view is increasingly taken by private owners of small forest properties that are intermittently managed by non-experts (Mostegl et al. 2019; Weiss et al. 2019). Active adaptation entails the use of silvicultural methods (e.g., tending, thinning, stand conversion, tree species enrichment) to change stand structures and tree species composition in ways that make the resulting forest better adapted to the climate that will exist during the life of the stand (Bolte et al. 2009; Millar et al. 2007). Re-deployment of the tools of silviculture for adapting current forests to climate change should be viewed as a necessity, given the rate of change predicted, which far exceeds the abilities of most tree species to move into new habitats (Hebda 1995; Settele et al. 2014).

Silviculturists recommend adaptive management that anticipates future site conditions and adapts the existing forests as depicted in Fig. 2 (Millar and Stephenson 2015). The upper panel shows a forest developing under the conditions of climate change until, at time  $t_2$ , a process is invoked that changes the characteristics of the forest. The previously existing stand no longer copes with local conditions and dies. After a time lag, a new stand develops that is better adapted to prevailing site conditions. The lower panel represents a pro-active management strategy. Knowledgeable foresters scrutinize the stability of the existing forests under the conditions of a changed climate and take counter-measures already at time  $t_1$ . In the presented example, the tree species diversity is enriched through the addition of species that are thought to be better adapted to projected future climatic conditions. Several tree species coexist until the less suitable tree species dies out at time  $t_3$ . After  $t_3$ , the adaptively managed stand (lower panel) is in an advanced state of development compared to the passively managed stand (upper panel). Figure 2 (upper panel) represents a likely scenario for unmanaged forests in which succession is the major driver. The upper panel also depicts a likely outcome for forests where a business-as-usual scenario of forest management is maintained, which was traditionally successful but is not suitable for future climate conditions.

Following, we illustrate strengths and weaknesses of old-growth forests as proxies for non-management and of managed forests for adaptation. Then, we present case studies on adaptation strategies of different intensities, including (i) non-management or passive adaptation, (ii) continuation of non-adaptive business-as-usual forest management, and (iii) active adaptation. We identify some effects of inaction on forest adaptation and provide some recommendations.

**Fig. 2** Possible pathways of forest development. In a zero-interaction scenario (upper panel), the existing forest develops until climate change effects trigger its collapse. On the deteriorated site, succession sets in and a new tree species composition develops. The previously dominating tree species fades out and the future forest is dominated by the target tree species (modified from Millar and Stephenson 2015)



## 2 Old-growth forests as template for a successful non-management option

The structure and dynamics of old-growth forests is used as reference system for managed forests. Old-growth forests are described as stands with large, old trees, dead wood on the ground, and no obvious human influence. In the absence of external influences such as stand-replacing disturbances, late successional tree species are dominant (Oliver and Larson 1990). Different definitions have been used, based on stand structure, successional state, or biogeochemistry (Spies and Franklin 1996; Wirth et al. 2009). A common property of old growth forests is heterogeneity. The characteristic complexity of old-growth forests due to the heterogeneity and diversity of stand structures is believed to make old-growth forests capable of adaptation to diverse and unexpected disturbances because the unmanaged forest can develop towards a variety of states, whereas the development options of managed forests are much narrower (Puettmann et al. 2009). Several authors have pointed out that old-growth forests continuously take up CO<sub>2</sub> in the biomass and soils over centuries (Luyssaert et al. 2008; Kutsch et al. 2009; Körner 2017; Zhou et al. 2006). But it is not clear whether this carbon sink function will decrease or even stop when the forests get into a steady-state of carbon sequestration in biomass and soil organic matter and of carbon loss due to decomposition of dead wood debris and soil organic matter (Desai et al. 2005; Pukkala 2017). Nevertheless, the concept of back-converting managed forests to untouched old-growth forests for the sake of climate change mitigation was readily adopted by nature conservation (Rapp 2003). A recent controversially discussed report valued the characteristics of non-managed forests, notably the carbon storage and the contribution to biodiversity and various ecosystem services, higher than the value chain from forest management to wood-based products and bioenergy and explicitly used old-growth forests as reference (EASAC 2017).

For forest managers, old-growth forests are in some cases a problematic reference. Some of the multiple beneficial effects are not convincingly demonstrated. Dynamics of forest ecosystems reflect natural mechanisms, but it is questionable whether the consequences of natural dynamics such as disturbances are all desirable. Old-growth forests are per se not resistant to disturbances. In the case of stand-replacing disturbances, old-growth forests disappear and can eventually redevelop (Wirth et al. 2009). Disturbances are an integral part of ecosystem dynamics; yet, they are problematic from an economical perspective and their consequences can be mitigated by specific actions of forest management. Moreover, including the carbon sink in long-living wood products and the substitution effects of wood use for replacing high-energy consuming materials (material substitution) as well as for replacing fossil fuels in energy production (energy substitution)

may favor managed forests with predominant use of wood-base products with high material substitution capacity over old-growth forests without wood use (Jandl et al. 2018a, b; Sathre and O'Connor 2010; Soimakallio et al. 2016). Nevertheless, sustainability principles in forest management need to be adhered to for avoiding unintentional effects such as a decline in biodiversity and critical reductions of the stand density (Schlesinger 2018; Sutton 2014).

Old-growth forests are not necessarily ensuring continuous forest cover. Depending on the forest type, old-growth forests can develop both along the schemes shown in Fig. 2. Some forest types such as Norway spruce (*Picea abies*) in the Alps tend to disintegrate in a late stage of their development, whereas European beech (*Fagus sylvatica*) forests tend to regenerate in the shade of the mature stand. And finally, old-growth characteristics of the stand structure do not ensure diversity of tree species. There are many examples of mono-species forest types for natural reasons, such as subalpine Norway spruce stands or green alder (*Alnus viridis*) stands along avalanche shoots where external forces are confining an ecosystem succession along consecutive seral states (Mayer 1974). Yet, in biomes that are allowing for mixed species forest old-growth stands can serve as inspiring templates for mixtures of trees species irrespective of their present commercial relevance.

Using characteristics of old-growth forests to increase the apparent naturalness of forests is only relevant in landscapes where the natural disturbance regime would have allowed old-growth forests to develop. The variation in the nature and commonness of 'old-growth' forests is evident in the forests of British Columbia (B.C.), which have been classified into Natural Disturbance Types, distinguishing ecosystems with rare, infrequent, and frequent stand-initiating events, and ecosystems with frequent stand-maintaining fires. Even in natural (i.e., uncut) conditions, old-growth forests are rare at sites with severe disturbances, and forests usually do not progress beyond the seral stage (usually lodgepole pine; *Pinus contorta*) before a stand-initiating fire. Therefore, using characteristics of old-growth forests to emulate natural forests would be artificial in these situations. Old-growth is more common in low-disturbance forests, located primarily along the coast of B.C., and gap-dynamics related to windstorm are the prevalent form of disturbance there (Bartemucci et al. 2002; Daniels and Gray 2006). Recognition of this prompted a change in forest management towards smaller openings and variable-retention harvest in coastal BC. This and other shifts in forest management to better emulate natural disturbance processes demonstrate the adaptability of forest management to changing paradigms. In Switzerland, half a century ago, several natural reserves have been taken out of forest management in order to re-establish forests with the characteristics of old-growth forests. An assessment of 25 such reserves has shown that the stand characteristics of old-growth forests are slowly approximated, particularly with respect to higher stand densities and a higher



abundance of giant trees, as compared to regularly managed forests. Disturbance events have initiated successional processes that are different from actively managed forests. In the case of bark beetle infestations, an active intervention is foreseen, even in natural reserves, in cases where the adopted measures are justified both with respect to effects and costs (Heiri et al. 2011; Heiri et al. 2012). The velocity of the conversion of stand characteristics from managed forests to old-growth forests is a process stretching over decades. The observed pattern in Switzerland is mostly re-affirming the conclusions of a pan-European meta-analysis where biodiversity increased slowly (Paillet et al. 2010).

### 3 Managed forests—more efficient in active adaptation of forests?

Forest sciences have, over a long period of observations and trial and error, developed strategies of using natural forest dynamics for optimizing stand development. Developing forest management has sometimes led to pitfalls such as site degradation caused by over-exploitation of forests (Perlin 1991). Key elements of forestry were curtailing unproductive periods and accelerating natural forest dynamics. In addition, forest managers make choices about tree species composition and maximize the use of available resources (Pretzsch et al. 2017). The advantages are numerous. In an unmanaged setting, the vegetation on a disturbed site would go through several successional stages and would reach a mature state after several decades. Managed forests can take up their productive role at an early successional stage, and successional stages can be abbreviated or even skipped. In the context of climate change, management can create conditions in a forest that alleviate some pressure on trees. Traditionally, the main purpose of forest management was timber production. However, forests can also be managed to optimize ecosystem services such as carbon sequestration in biomass and soil. Of utmost importance are substitution effects where wood products are replacing other material with a larger ecological footprint (Braun et al. 2016; Pukkala 2017; Smith et al. 2016; Soimakallio et al. 2016).

Referring to Fig. 2, the intention of forest management is avoiding the time span between  $t_2$  and  $t_3$ , where the soil is exposed and the site is unproductive. There are several attempts how characteristics of old-growth forests have been introduced in managed forests. The ancient concept of ‘Plenterforest’ is characterized by a continuous forest cover, the immediate proximity of different tree species at different stages of their development, an uneven age distribution without distinct age classes, and an uneven vertical structure (Fig. 3). It had its origin in forests that were managed by farmers and was adopted as a silvicultural concept by Henry Biolley in the late nineteenth century in Couvet, Switzerland. The concept is successfully applied in Switzerland, Germany, and Slovenia, primarily in fir-spruce-beech forests, and has been extended to pine forests in the USA (Guldin et al. 2017). The risk from biotic and abiotic disturbances is distributed among many stand members. However, devising a long-term management concept for this type of forest is complicated. Similar management systems exist under the name of continuous-cover-forestry (Pommerening and Murphy 2004) and target-diameter harvesting (Reininger 1987).

## 4 Case studies

In the following, we discuss the options of active and passive adaptation and their combination in order to adapt forests to climate change based on five cases from the temperate and boreal zones. Passive adaptation focuses on the utilization of natural forest dynamics for forest adaptation which can be thus regarded as congruent element of non-management (cf. Bolte et al. 2009). We confine our assessment to cases where the authors have first-hand access to experimental data. Cases from other biomes such as the atlantic deciduous forests in France, Mediterranean forests, and others are not included, but may be characterized by a similar descriptive approach.

### 4.1 Old growth beech forests—passive adaptation is an option

European beech is the major tree species of the natural forest vegetation in large parts of central and Western Europe (Bohn



Fig. 3 Idealized Plenterwald as proxy for structural diversity in managed forests

et al. 2004; Leuschner and Ellenberg 2017). However, since medieval times, natural beech forests were removed for or devastated by agricultural land use, and in the last centuries, remaining beech forests were often transformed into more productive coniferous forests with Norway spruce or Scots pine (*Pinus sylvestris*) (Bolte et al. 2007). In its natural range, European beech, as a shade tree and late-successional species, is highly competitive to other native species and exhibits a low vulnerability to biotic threats. A broad ecological range of mesic sites would be dominated by rather pure beech forests without human intervention (Leuschner and Ellenberg 2017). Currently, beech's reputed high drought sensitivity (e.g., Gessler et al. 2006) is under debate, and there are recent studies demonstrating its high potential through local adaptation to drought and high phenotypic plasticity (Bolte et al. 2016; Stojnic et al. 2018). Old-growth beech forests in Central Europe that are remnants of the natural forest community and position are highly self-regulating ecosystems (Fig. 4). Possible replacement species under drought like native oak species (*Quercus petraea*, *Q. robur*) are vulnerable to pathogens (Bergot et al. 2004) and submediterranean or even mediterranean tree species exhibit under current climate conditions a low competitive vigor and low frost tolerance (Hickler et al. 2012b). Thus, due to absence of promising measures of active adaptation and current high resilience of beech forest systems, mainly passive adaptation appears to be feasible using natural forest dynamics and possible succession for forest adaptation to climate change. This may be supported by the modest admixture of drought-tolerant provenances of European beech and less abundant native species like small-leaved lime (*Tilia cordata*), hornbeam (*Carpinus betulus*), or native *Sorbus* and *Acer* species. For economic reasons, native and non-native conifer species like Silver fir (*Abies alba*), Douglas-fir

(*Pseudotsuga menziesii*), or Grand fir (*Abies grandis*) could be of interest, however only supporting and not replacing natural succession processes.

#### 4.2 Timberline forests in the Alps—Low intensity management with active and passive elements maintain a sensitive ecosystem

In the Inner Alps, Cembran pine (*Pinus cembra*) has a narrow habitat and is the naturally dominating tree species at the upper timberline (Fig. 5). Many Cembran pine forests have been replaced with subalpine pastures approximately 150 years ago, but with the demise of their economic relevance, the pine forest is re-gaining its natural habitat. Owing to climate change, the habitat of Cembran pine is expanding (Dullinger et al. 2004; Körner 2007; Zeng 2010). Cembran pine is presently not vulnerable to bark beetle attacks. Major threats are fungi for immature trees and damages from deer and chamois due to insufficiently controlled animal densities (BAFU 2010). The productivity of Cembran pine forests is low and even the stimulation of growth by higher temperatures and longer growing seasons will accelerate the productivity to a level that is still below economically viable levels (Jandl et al. 2018a, b). Cembran pine forests are slowly growing, are extremely stable, and have lifespans of several centuries. Low intensity management will not affect the forest functions.

On privately owned land forest management, decisions are mostly made by the farmers themselves. The owners are forced to cope with increasing production costs under naturally challenging conditions (Streifeneder et al. 2007). Forest practitioners are advised to continue the present

**Fig. 4** Near-natural beech old-growth forest with natural regeneration in southern Sweden. Picture A Bolte



**Fig. 5** Cembran pine forest in the Oetz Valley at the upper treeline in Tyrol. Picture R. Jandl



low intensity forestry of salvaging trees from natural mortality and to ensure the re-juvenation of the stand in eventually opening gaps in the canopy. Thereby the main function of the forest, i.e., the protection of infrastructure, can be maintained with minimum changes in the management structure. The recommended silvicultural interventions can be rare events and may be decades apart. This view is representing the current mindset of land managers in the Central Alps. In multi-criteria analysis, regionally active experts in agriculture, forestry, nature conservation, and tourism were asked to evaluate different ecosystem services. Unanimously, the protection against natural hazards was valued the highest. Foresters valued biodiversity and regulatory services equally highly, whereas forest productivity and esthetics played a minor role in land-use decisions (Fontana et al. such as the Cembran pine forests are potentially unmanaged forests where inaction does not lead to currently foreseeable problems). Nevertheless, the value of the extracted timber will not cover the incurred management costs in poorly accessible high-elevation forests. Consequently, accessibility for vehicles is a strong determinant for land-use intensity in high elevation forests. Such a setting is conducive for focusing on the provision of additional ecosystem services besides protection against natural hazards. High-elevation forests are harboring a rich diversity of plants and animals and are shaping the scenic beauty of rugged mountain landscapes. The biodiversity is highest at the interfaces of subalpine pastures, shrublands, and forests. The aggradation of forests that are moving back into abandoned pasture lands are even decreasing the floral diversity (Tasser and Tappeiner 2002).

### 4.3 Secondary spruce in Central Europe—vulnerable forests require substantial active adaptation

‘Secondary spruce forests’ describe sites where the tree species of the potential natural vegetation have been replaced by Norway spruce. Obviously, the tree species composition of these forests is defined by management decisions. Secondary spruce forests have been established since the late 1800s in Austria, Switzerland, and Southern Germany mainly at low elevation sites (e.g., Fig. 6). At most sites, spruce is the dominant or co-dominant species of a mixed-species forest. The main incentive was the superior productivity of Norway spruce in comparison to autochthonous, mostly deciduous trees such as oak and beech. The forests were always to a greater extent affected by disturbances such as storm damages, bark beetle outbreaks, and stem rot than natural mixed-species forests. However, economic losses due to regional damages were compensated by the overall gain in forest productivity. In many regions of Central Europe, these forests form the backbone of the forestry sector. Consequently, their productivity and the management schemes are well investigated (Assmann 1961; Pretzsch 2010).

The need for transferring secondary spruce forests into biologically more diverse mixed-species forests or deciduous forests is only reluctantly accepted by forest practitioners. Reasons are that mixed species stands are often less productive than pure Norway spruce stands and that the industry specifically demands timber from Norway spruce for technological reasons. Some expectations are resting on the genetic diversity of spruce. Provenance trials have confirmed that spruce grows on a wide range of site conditions. Provenances that are tolerant towards warm and dry





**Fig. 6** Secondary spruce forest in Lower Austria. The spruce-dominated stand is approximately 80 years old. In the understory layer, deciduous tree species are regenerating. Picture R Jandl

conditions may keep the window for spruce management open under future climate conditions. In addition, Silver fir is seen as option at sites that are unsuitable for Norway spruce (Kapeller et al. 2012; George et al. 2015).

Upon the establishment of secondary spruce forests, it is clear that several interventions are required during the entire rotation period in order to maintain the intended dominance of spruce. Figure 6 shows that deciduous trees are vigorously developing in the understory. These species would be abundant in the mature phase when left to natural dynamics. Switching to a zero-management approach translates into the loss of control of future forest development. The often even-aged spruce-dominated forests are more vulnerable towards infestations by bark beetle. Even perfectly maintained experimental stands are susceptible (Fig. 7). Forest health considerations call for immediate action involving the removal of

affected trees and neighboring trees within a certain area. Leaving the area unmanaged would stimulate a further expansion of bark beetle. The removal of tree groups after bark beetle infestations is highly problematic for forest managers. It defines the location, spatial extent, and timing of harvesting operations and overrides forest management plans. The management decisions are no longer driven by ecological and economic considerations but are mostly reactive (Lexter et al. 2015; Thom et al. 2016).

Besides the immediate need to combat the spread of pests and pathogens, the strategies of adaptive forest management are numerous. It is possible to amend the forests with additional species, and thinnings can improve the water availability for individual trees. Even the rotation period can often be reduced because longer growing seasons allow reaching target dimensions of the timber market earlier. However, with

**Fig. 7** Bark beetle infestation in Waldviertel/Lower Austria in 2018. After a mild winter and long dry spells during the growing season, heavy bark beetle infestations were recorded. Picture G Steyrer





today's knowledge and the concerns regarding the effects of climate change, the establishment of secondary spruces forests would be difficult to justify.

#### 4.4 Mountain conifer forests in the Alps—few options for required adaptive measures

Coniferous forests of the montane zone are the back bone of forestry in the Alps and have a high relevance for the economy in rural areas. Owing to climatic and topographic restrictions, there are no alternative land uses to forestry. Besides their role as timber providers, mountain forests are an integral element of the protection of the population and infrastructure against natural hazards. Other than in secondary spruce forests of lowlands, mountain forests of the Alps are often naturally dominated by Norway spruce. High productivity despite a low nutrient supply from soils and a harsh climate has fostered Norway spruce-dominated forests (Fig. 8). Mountain forests are extremely vulnerable because bark beetle outbreaks still take forest managers by surprise in previously unaffected areas (Jandl et al. 2013). In the case of the loss of protection forests in mountain regions, technical protection measures would be immediately required at substantial costs (Lexer et al. 2015). Besides biotic damages, the productivity of Norway spruce forests is declining due to spring and summer droughts. In many regions, there are only few reference stands where alternative species such as Silver fir, European larch (*Larix decidua*), and deciduous trees are currently dominant. Adaptive forest management concepts including additional tree species are therefore rather speculative and not supported by results of field trials. The proven strategies of adaptive

management are therefore confined to growing space regulations and shortening of the rotation period.

#### 4.5 Lodgepole pine forests of British Columbia—active adaptation to restore forest functionality

The forests of British Columbia (B.C.), Canada, provide a contrasting case study when considering adapting forest management practices in the face of climate change. Most forests in B.C. are first-growth and the distribution of tree species reflects the current or past climate. This relationship is reflected in the biogeoclimatic classification of B.C. forests, which underlies all forest management decisions in the Province. Most sites are regenerated naturally or artificially with the species that occur naturally on the site, so second-growth forests also reflect current and past climates. Models have been developed to predict future climate envelopes and future optimal distributions of tree species in B.C. as related to climate (Hamann and Wang 2006). The distances involved in these climate envelope shifts make it unlikely that the species could make the necessary range shifts without assistance. In this situation, both the passive and business-as-usual scenarios carry the risk that the species present on a site in a few decades may not be well adapted to the site conditions. Such effects are already apparent in the decline of yellow cedar (*Cupressus nootkatensis*) at the lower extent of its past elevation range (Hennon and Shaw 1994), and the ongoing death of red-cedar (*Thuja plicata*) trees on dry sites within its current range (Wilson and Hebda 2008). Active adaptation would entail a revision of planting guidelines to reflect future site conditions

**Fig. 8** Mountain Norway spruce forest in Styria, Austria. The forests are widely dominated with Norway spruce. Picture R Jandl



rather than past. Wang et al. (2006) used data from lodgepole pine provenance trials across B.C. and the climate model, ClimateBC, to evaluate seed deployment options in light of climate change predictions for B.C., and provincial seed transfer guidelines have been modified to allow for planting of genotypes outside of their current range (Aitken et al. 2008).

Effects of changes in climate on disturbance regimes (both biotic and abiotic) have been acutely apparent in lodgepole pine forests of B.C. in the last two decades. Vast areas of almost pure, mature lodgepole pine occurred throughout the interior of the Province, which have been linked both to fires set during European settlement and fire suppression policies (Burton 2008). Wildfires have occurred in increasing number and intensity throughout the interior of B.C., with 2018 recently surpassing 2017 as the worst wildfire year on record in B.C. The outbreak of the mountain pine beetle (MPB; *Dendroctonus ponderosae*), which affected over 18 million hectares of forest and caused the loss of about 742 million m<sup>3</sup> (> 50%) of the merchantable pine volume in BC alone (<https://www.nrcan.gc.ca/forests/fire-insects-disturbances/top-insects/13397>), has been attributed to warmer winters associated with climate change (Creeden et al. 2014). Unprecedented levels of damage by needle blight, caused by the fungus *Dothistroma septosporum*, in regenerating lodgepole pine stands have also been attributed to climate change (Woods et al. 2005). Multiple chronic stress agents linked with climate change have also been implicated in the increase in mortality, damage, and disease in pine-leading stands in B.C. (Mather et al. 2010; Woods et al. 2016). Passive approaches to management (i.e., to 'let-it-burn' or un-controlled insect populations) have enormous ecological and economic implications for the health of forests and the timber supply across millions of hectares of the Province. Given the serotinous nature of lodgepole pine cones, allowing nature to take its course is likely to result in perpetuation of vast areas of almost pure lodgepole pine, which would be susceptible to further insect and disease outbreaks. Business-as-usual also carries unacceptable risk, as past experience is becoming increasingly irrelevant to current and projected future site conditions. Adaptive management such as silvicultural interventions to increase species diversity at the stand or landscape level, or prescribed fires to reduce susceptibility to severe wildfire, could improve the health and longevity of pine forests. In fact, the growing unpredictability of forest development has prompted a call for a new forest management paradigm in B.C., in which the goal of management interventions is not to reach a precise objective but instead to ensure that the forest has all of the elements necessary to continue to adapt and to produce desirable goods and services in the future (Woods et al. 2016). Intelligent and active management of B.C. forests is arguably more critical now than in the past.

## 5 Conclusions

Climate change calls for adaptive forest management. The uncertainty of the extent of climate change and the responses of forests, and the limits of interpretations of climate-change experiments leave forest managers with a wide range of practical options, but few clear-cut recommendations for management decisions. Whereas forestry professionals are familiar and comfortable with decision making within wide margins of evidence, lay-persons may be overwhelmed by the lack of guidance. The increasing number of non-expert forest owners of small forest properties finds itself in an unexpectedly difficult situation when making decisions on forest management with long-term implications.

Many forest ecosystems have been shaped by human influence and tree species composition and stand structure have been managed with hindsight to well-defined societal expectations. Managers of private forests can satisfy many expected ecosystem services emerging from forests, but still need to meet ends when balancing the costs of forest management with revenues from timber sales. A trade-off between the provision of public goods and commercial interests is required. We identified several case studies for which we assessed the degree of necessary adaptive interaction in order to cope with climate change. In only a few forest types are we confident that continuation of business-as-usual management or adoption of a passive non-management approach will yield satisfactory results. Our examples for this case are mature beech forests and subalpine pine forests that are presently stable ecosystems that are not affected by immediately obvious climate-change-related threats. In many productive forests that are supporting the bio-economy in rural areas, adaptation of forest management to climate change is recommended. The tree species and age class distribution of production forests often deviate from forests that which would have developed without human engagement. Relying solely on natural mechanisms that regulate the effects of climate change is risky. There is already evidence that traditional concepts of silviculture are insufficient to prepare the forests for future conditions. Changes in the tree species composition, rotation period, and stand density are required. In low-elevation forests, a wide range of adaptive forest management concepts is available and foresters can choose among several options. At sites with nutrient limitations, as commonly encountered in mountain regions, the range of available options for adaptive forest management is narrower. In particular, there are either fewer tree species available that could replace the existing dominant tree species, or there is limited experience with tree species that could be used as stand-dominating trees. For many of these forests, there are few if any reference stands that reflect conditions of pristine forests without human interaction. It is therefore often impossible to use unmanaged reference forests as a benchmark for the most appropriate strategy of adaptive forest management. Foresters will therefore need to

use both experience and imagination to devise suitable adaptive management plans for future forests.

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## Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflict of interest.

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