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Assessing transformation scenarios from pure Norway spruce to mixed uneven-aged forests in mountain areas

Torben Hilmers[1] · Peter Biber[1] · Thomas Knoke[2] · Hans Pretzsch[1]

Abstract

Mixed mountain forests, primarily made up of Norway spruce (*Picea abies* (L.) Karst.), silver fir (*Abies alba* Mill.) and European beech (*Fagus sylvatica* L.), cover about 10×10^6 ha of submontane–subalpine altitudes in Europe. They provide invaluable ecosystem services, e.g. protection against avalanches, landslides or rockfall. However, pure Norway spruce stands have, since mediaeval times, been heavily promoted as productive stand types for salt works at sites naturally supporting mixed mountain forests. Damage to these secondary pure spruce stands has been steadily increasing in recent decades. Furthermore, due to their previous limitation due to low temperatures and a short growing season, forest ecosystems in higher elevations are expected to be strongly affected by climate warming. To address these problems, alternative management concepts are being intensively discussed. A possible option to improve the stability and resilience of the stand is the transformation from pure Norway spruce stands into site-appropriate, sustainable and stable mixed mountain forests. In this study, we have tested seven different transformation scenarios (e.g. slit, shelterwood and gap-coupes, strip clear-cutting, do-nothing) and their impact on five evaluation criteria (forest growth, economics, carbon sequestration, (stand) stability and biodiversity). As there are hardly any practical examples for some of the transformation scenarios available, we have used the forest growth simulator SILVA to assess whether the tested transformation scenarios differ in transformation success and to observe trade-offs between the criteria of evaluation. Of the investigated scenarios, we consider the ones with gap or slit-coupes with the most beneficial overall utility values for the portfolio of the five evaluation criteria. However, we showed with our results that it is possible, by means of several trajectories, to return destabilised forests to sustainable and stable systems. We showed that a transformation is realistic, even if sophisticated silvicultural concepts are not strictly pursued.

Keywords *Picea abies* (L.) · Pure stands · Transformation · Mixed mountain forests · Evaluation criteria

✉ Torben Hilmers
torben.hilmers@tum.de

1 Chair for Forest Growth and Yield Science, TUM School of Life Sciences Weihenstephan, Technical University of Munich, Hans-Carl-Von-Carlowitz-Platz 2, 85354 Freising, Germany

2 Institute of Forest Management, TUM School of Life Sciences Weihenstephan, Technische Universität München, Hans-Carl-von-Carlowitz-Platz 2, Freising 85354, Germany

Introduction

In addition to the often promoted Norway spruce (*Picea abies* (L.) Karst), mixed mountain forests also comprise silver fir (*Abies alba* Mill) and European beech (*Fagus sylvatica* L.). In the following, we refer to these tree species as spruce, fir and beech, respectively: They can successfully coexist in altitudes between ~600 and 1400 m above sea level and account for the largest potential share of natural forests in Southern Central Europe (Moning and Müller 2008). More than half of Central Europe's surface area consists of mountain areas, which is where most of the existing forests are concentrated (CIPRA 2007).

The presented problem and solution of transforming from artificial to close-to-nature forest is of general importance for the forest management of mountain forests worldwide (Kimmins and Blanco 2011). However, particularly

in mountainous areas, forests are of great ecological and socio-economic importance in Central and Eastern Europe due to their provision of various ecosystem goods and services (e.g. Ellenberg 1988; Forest Europe 2011; Pretzsch et al. 2015; Mina et al. 2017). The strong topographic gradients and high relative relief strongly increase the propensity for soil loss through erosion (Panagos et al. 2015), as well as gravitational processes such as rockfall, avalanches and snow gliding (Rammer et al. 2015; Leitinger et al. 2018). Furthermore, mountain topography often facilitates heavy local precipitation events and thunderstorms, and human infrastructure is often restricted to flood-prone river valley bottoms. As a consequence, the green infrastructure provided by forests is particularly relevant in mountainous countries. Due to their importance in buffering against the consequences of harsh mountain environments, mountain areas frequently have a substantially higher forest share than low-elevation areas (EEA 2010). They constitute regional hotspots of forest C storage (Nabuurs et al. 2008) and are estimated to contain 11% of current global biomass stocks (Erb et al. 2018). In addition to providing regulating services to local communities, mountain forests are thus also relevant for the global climate system.

Spruce, fir and beech have coexisted for thousands of years in mixture without active management or with close-to-nature forestry across this region (Magin 1959; Preuhsler 1979). Interactions between the three species according to the literature seem to be balanced, i.e. the interactions are neither one-sided against or in favour of one of the three species (Pretzsch et al. 2015). For example, in spring conifers may benefit from the neighbourhood of leafless beech by already growing with improved access to water (Goisser et al. 2016; Rötzer et al. 2017). During the common growing season, however, the deeper roots of beech and fir (Lebourgeois et al. 2013) can provide better water supply at the expense of the shallow-rooted spruce. Moreover, in mixed mountain forests spruce and fir are typically higher than beech and can pre-empt the light due to their occupation of the upper canopy layer (Pretzsch et al. 2015). On the other hand, the high morphological plasticity enables beech to more quickly occupy the empty space in case of disturbances (Bayer and Pretzsch 2017).

Both conifers reflect an isohydric strategy (Lyr et al. 1992) and show higher stem and root growth during prolonged time spans under drought than beech (Leuschner 2009; Nikolova et al. 2009). While the hazardous behaviour of the anisohydric beech can lead to tree mortality under the impact of extreme water shortage, the behaviour can be beneficial when water is abundant or moderate drought stress (e.g. Klein 2014). There are more structural and functional traits such as crown plasticity (Jucker et al. 2015; Forrester and Albrecht 2014), rooting depth (Rothe 1997; Schmid and Kazda 2002), litter decomposition (Rothe and Binkley 2001)

and browsing pressure (Ammer 1996) that prevent any one of the three species from becoming a permanent winner or loser, and despite their effects changing with climate and growing conditions, the balance between the tree species is maintained.

In terms of stand growth, Hilmers et al. (2019) found that mixed mountain forest ecosystems are rather resilient against disturbances such as acid deposition, climate warming and ozone. As growth reductions in one of the three species were compensated by a growth increase in the others, the stand productivity of mixed mountain forests of spruce, fir and beech in total has hardly changed over the last 30 years. One possible reason for this finding is that the potential damages are rather equally distributed, with late frost and ozone susceptibility of fir and beech (Larsen et al. 1990; Matyssek et al. 2010), the high sensitivity to smoke damage and acid deposition of fir (Elling et al. 2009), the high risk of bark beetle (Wermelinger 2004) and snow and storm damage (Spiecker 2000) of spruce. This temporal, spatial and functional complementarity and risk distribution may contribute to the overyielding of spruce and beech (Pretzsch et al. 2010; Rothe 1997), spruce and fir (Jensen 1983; Pretzsch et al. 2010; Vallet and Pérot 2011; Forrester and Albrecht 2014), and spruce, fir and beech (Pretzsch and Forrester 2017; Mina et al. 2018).

However, mixed mountain forests have often suffered a reduction in species richness. In the German Alps, for instance, spruce has, since medieval times, been heavily promoted as a productive timber species for salt works at sites naturally supporting mixed mountain forests (Seidl et al. 2007). Damage to these secondary pure spruce stands, however, has been steadily increasing in recent decades (e.g. Briner et al. 2013). These forests are particularly vulnerable to summer droughts (Lévesque et al. 2013; Zang et al. 2014), extensive bark beetle outbreaks (Seidl et al. 2014) and pathogens (Porta et al. 2008). All are then further favoured by a warmer and possibly drier climate (e.g. Matulla et al. 2002; Lexer et al. 2002; Pepin et al. 2015). Marini et al. (2012) found that forest disturbance in the European Alps was seven times higher where spruce was planted in sites that were warmer than those within its historical climatic range. However, the importance of whether spruce grows within or outside its native range is decreasing as climate conditions are changing rapidly. Climate change-driven disturbances threaten spruce over virtually its entire range in Europe, and some recent disturbances have, for instance, already reached native subalpine spruce forests close to the timber line in the Alps (Hlásny et al. 2019). In addition, the repeated cultivation of pure spruce stands has a negative effect on soil fertility (Seidl et al. 2007).

To address these problems, alternative management methods are being intensively discussed (Reininger 2000; Spiecker et al. 2004; Löf et al. 2010). A possible option

to improve the stability and resilience of the stand against abiotic and biotic disturbing factors, as well as to increase productivity, is the transformation of pure spruce stands to site-appropriate mixed mountain forests (Spiecker et al. 2004; Seidl et al. 2011; Pretzsch and Forrester 2017; Hilmers et al. 2019). This transformation has two aspects: (1) a change in the species composition from pure to mixed stands and (2) a change in the stand structure from regular, even-aged stands to more complex, uneven-aged stands.

The advantages of more complex forest stands, for example their higher stability against various disturbances and their superiority regarding many ecosystem services, attract attention (Bauhus et al. 2017; Bravo-Oviedo et al. 2018). Thus, at present there is a tendency towards transformation of age-class monocultures to continuous covered forestry worldwide (Vitkova and Dhubháin 2013). An important argument for fostering more diverse forests, containing both early- and late-successional species, is the insurance hypothesis. This states that diverse ecosystems are better buffered against disturbances (have higher resistance) and recover more quickly (have higher resilience; Jactel et al. 2009). Species diversity can mean risk distribution in view of abiotic and biotic disturbances, stability of growth and permanent protection function (soil erosion, avalanches, flooding). Such mixtures recover considerably faster from disturbances than other ecosystems, due to their elevated response diversity. Moreover, higher stand diversity is positively associated with the supply of many ecosystem services.

The state-of-the-art silvicultural approach in the Alps consists of small, irregular patch cuts for regenerating the forest and maintaining a high level of forest canopy cover in space and time (Cordonnier et al. 2008; Streit et al. 2009). It aims at the supply of regulating services and maintaining a relatively continuous forest cover, while enhancing resistance and resilience to disturbances (Dorren et al. 2004; Brang et al. 2006). However, management is complicated by steep terrain and low accessibility, which requires highly specialised harvesting technologies, (e.g. cable line systems) and results in high management costs (Valente et al. 2014; Jandl et al. 2018). As an alternative, one could adopt a more differentiated strategy, maintaining the existing mixed mountain forests, but transforming pure spruce stands to mixed mountain forests of mainly spruce, fir and beech. Such a strategy is already applied by some forest enterprises (e.g. Bayerische Staatsforsten AöR 2018).

There are hardly any existing practical examples for both maintenance and transformation. Thus, simulations with the forest growth simulator SILVA 2.3 (Pretzsch and Kahn 1996; Pretzsch et al. 2002) served as a supporting tool to assess whether the tested transformation scenarios are successful. Growth models integrate the knowledge about the growth of trees and stands; they can reproduce the growth behaviour of stands with which parameters

have been set. After appropriate calibration and validation, however, they are also suitable for reproducing stand development for which there are no sample or illustrative examples yet. For example, simulation models can be used to simulate the consequences of new types of thinning, creation of infrastructures or climate change. The prerequisite for this is that the model internal growth functions reproduce the tree and stand reactions for a broad spectrum of competitive and neighbourhood situations, as well as site conditions, in a biologically plausible way. If this is the case, models can effectively contribute to the development of new management guidelines for forest management in the high mountains (Pretzsch 2019). Besides the state-of-the-art silvicultural approach in the Alps, however, other silvicultural systems (e.g. gap and strip clear-cut-coupes) were to be compared on multiple criteria.

In addition to topics in numerous studies on the economic aspects of forest transformation (Knoke et al. 2001; Hanewinkel 2001; Knoke and Plusczyk 2001; Knoke et al. 2008; Roessiger et al. 2011; Messerer et al. 2017; Beljan et al. 2018), we investigated the effects of forest transformation on the habitat complex of mixed mountain forests taking a holistic approach. In this sense, the present contribution was devoted to the evaluation of multiple criteria of different forest transformation systems of secondary pure spruce stands, taking into account the criteria of forest growth, economics, carbon sequestration, stand stability and biodiversity. Wood production (forest growth, economics) provides renewable raw materials that are in high demand and wood production jobs are maintained therewith (Sikkema et al. 2011; Hetsch 2008). Carbon sequestration contributes to the mitigation of climate change and can be fostered through both afforestation and forest management (Naudts et al. 2016). Stand stability is fundamental for providing regulating services to society (Moos et al. 2018; Altieri et al. 2018), and biodiversity is likely to play a key role in mediating the relationship between plants and ecosystem processes by influencing the physiology, activity and population dynamics of plants (Weisser and Siemann 2013). The selected criteria are strongly related to the criteria for ecological, economic and social sustainable forest management (MCPFE 1993) which include the care for (1) forest resources, (2) forest ecosystem health and vitality, (3) productive functions, (4) biological diversity, (5) protective functions and (6) socioeconomic functions.

The specific objectives of the contribution were (1) to identify possible paths that can be followed to transform characteristic pure spruce stands into semi-natural mixed forests at equilibrium using different forest management scenarios and to evaluate (2) if the investigated management methods yield stable stands over the long run; and (3) how the different scenarios differ in terms of forest

growth, economics, carbon sequestration, stand stability and biodiversity.

Materials and methods

Secondary pure spruce forests

Starting point for the simulations was formed by a total of 30 different pure spruce stands (Table 1), which were generated by the structural generator, STRUGEN (Pretzsch 1997). Initial data for the simulation and the assumed site productivity were deduced using inventory data of forests in the Bavarian Alps. All the simulated plots covered 2 ha each, at an age of 30 to 40 years, on sites of the 'Oberbayerische Flyschvoralpen' (800–1200 m above sea level, good site conditions). Single-layered initial stands were characterised by an average basal area of 32.8 m^2 ha^{-1} with an average volume of the remaining stands of 181 m^3 ha^{-1} (Table 1).

Silvicultural goals

Assuming the help of cable yarding operations, these pure spruce stands were to be transformed to semi-natural mixed mountain forests of beech, spruce and fir at equilibrium. These multi-layered mixed mountain forests should have a mixture of 30–40% of species other than spruce and, if at equilibrium, an exponentially decreasing stem distribution. In addition, this forests should be uneven-aged, show a high structural diversity as well as an advanced regeneration layer, containing both early- and late-successional species, on as large an area as possible. By regular moderate treatments, the volume of the remaining stand is kept on an optimal level, so that the desired structural diversity and a continuous natural regeneration are obtained. While on rich sites, a volume of the remaining stand of 400–500 m^3 ha^{-1} is aimed at, a volume of the remaining stand of 300–400 m^3 ha^{-1} is targeted on mesic sites. In order to avoid growth reduction, the respective lower value should not be undercut over a longer period of time. Very poor sites were not taken into account, as regular management often takes a back seat in these areas and aspects of forest conservation and protection forest management are in the foreground.

Silvicultural scenarios

The state-of-the-art silvicultural approach in the Alps (e.g. Bayerische Staatsforsten AöR 2018) is intended to aim at transforming secondary pure spruce stands into semi-natural mixed forests at equilibrium. To sustain the unique functions and services of mixed mountain forests, the natural gap dynamics of mountain forests are emulated by silviculture (e.g. Acevedo et al. 1996; McCarthy 2001; O'Hara 2001; Ciancio et al. 2006). In this context, the most common silvicultural prescription for management is the combined shelterwood and femel-coupe system, which is composed of several stages: spruce stands at the age of 40–60 years are slightly opened up homogeneously over the whole stand area to promote natural regeneration and stability (shelterwood-coupe). Above these patches of forthcoming regeneration, the canopy is opened up continuously or removed completely in one pass (femel-coupe) and missing tree species are planted. In the areas between the regeneration slits, only very cautious interventions (target diameter harvest) take place in order to maintain the volume of the remaining stand between 400 and 500 m^3 ha^{-1} depending on site conditions. With the progressing regeneration of all three species, the regeneration slits are gradually extended by harvesting trees at the edges during the femel-coupe. By removing the overstorey step by step, 40–60 years after the first harvest, the whole stand area is regenerated as the regeneration patches grow together. Except for the initial shelterwood-coupe, any remaining thinning operations always only take place on every second cable line. After two operations on the same cable lines, the cable lines are changed. Thus, only half of the area is worked at a time, and the creation and expansion of the regeneration slits take place at different times. This procedure ensures that a heterogeneous vertical structure is created and that the cable lines can also be used over long periods of time. In order to validate the state-of-the-art silvicultural scenarios, the evaluation of multiple criteria was also applied to conventional management methods, such as strip clear-cut and gap-coupe (Mosandl 1984; Table 2).

From silvicultural guidelines to scenario simulation

All simulations for stand development and timber production were carried out with the single-tree, distance-dependent forest growth simulator, SILVA 2.3 (Pretzsch and Kahn 1996; Pretzsch et al. 2002). Due to the partly stochastic character of SILVA, every simulation run can, despite identical starting conditions and treatment programmes, produce different results. Since the regeneration phase, in particular, provides crucial information for forest transformation concepts, SILVA also includes a regeneration module. Simulations with SILVA were performed as sequences of five-year time steps. In order

Table 1 Key forest growth data of the simulation stands

Species	Age (years)	N (n ha^{-1})	hg (m)	dg (cm)	Basal area (m^2 ha^{-1})	Volume (m^3 ha^{-1})
Spruce	30–40	2486 ± 92	10.7 ± 0.25	12.2 ± 0.25	32.8 ± 1	181.6 ± 12

N, stem number per hectare; dg, diameter of mean basal area; hg, mean height corresponding to dg

Table 2 Simulation scenarios, their short description and references for detailed information on the simulated forest transformation scenarios

Code	Scenario	Brief description	Regeneration	References
DN	Do-nothing with natural regeneration	No treatment	Natural regeneration	
G	Gap-coupes with planting	Clearance of gaps with a radius of 30 m. Change of cable lines every 20 years. First operation at stand age of 35 years. Afterwards, the stand is cleared in strips	Planting of fir and beech in gaps + natural regeneration	Mosandl (1984)
SH1	Shelterwood-coupes with natural regeneration	Partial clearance of slit-like patchy gaps (width: 30, length: 25). Change of cable lines every 20 years. First operation at stand age of 35 years	Natural regeneration	Bayerische Staatsforsten AöR (2018)
SH2	Shelterwood-coupes with planting	Partial clearance of slit-like patchy gaps (width: 30, length: 25). Change of cable lines every 20 years. First operation at stand age of 35 years	Planting of fir and beech under shelter in the patchy gaps + natural regeneration	Bayerische Staatsforsten AöR (2018)
SL1	Slit-coupes with natural regeneration	Clearance of slit-like patchy gaps (width: 15 m, length: 30 m). Change of cable lines every 20 years. First operation at stand age of 35 years	Natural regeneration	Streit et al. (2009), Bayerische Staatsforsten AöR (2018)
SL2	Slit-coupes with planting	Clearance of slit-like patchy gaps (width: 15 m, length: 30 m). Change of cable lines every 20 years. First operation at stand age of 35 years	Planting of fir and beech in the slits + natural regeneration	Streit et al. (2009), Bayerische Staatsforsten AöR (2018)
SC	Strip clear-cutting with natural regeneration	Clearance of the stand in strips. Strip width 30 m. Distance between the strips 120 m. First intervention at age 80. Interval between interventions 20 years	Natural regeneration	

to cover an overall simulation time span of 150 years, we simulated 30 such five-year periods in each run. This means that the development of an entire forest life cycle could be simulated. In addition, the 'silvicultural treatments' (e.g. gap, femel and shelterwood-coupe) and 'creation of infrastructures' (e.g. cable crane and cable lines) modules were supplemented for the present comparison of different silvicultural scenarios. The results of the wood sorting were calculated using the SorSim program (Lemm et al. 2013). Cable lines, femel gaps and planting were created outside the simulator using the data handling features of the R software (R Core Team 2018). The stored carbon quantities in wood products, and the substitution of stored carbon by the energetic use of biomass, were calculated using a harvested wood products (HWP) model from Klein et al. (2013). Comparisons of the results of the different silvicultural scenarios were made using R (R Core Team 2018), specifically employing the dplyr package (Wickham et al. 2018).

Validation of the simulation results

The simulation results were finally compared with the results from long-term experimental plots. For the validation, data from two sets of long-term experimental plots were used. On the one hand, we used data from 22 mixed mountain forests long-term experimental plots comprising beech, spruce and fir at elevations of between 850 and 1240 m a.s.l. in the catchment area of the Northern Limestone Alps in Bavaria (Southern Germany). These plots were established in order to investigate the influence of different silvicultural treatments (femel-shelterwood-coup) on the regeneration dynamics and volume increment and were established in the 1970s (Pretzsch et al. 2015). Moreover, we have compared our results with data from 14 long-term experimental pure spruce plots on high-performance sites in southern Bavaria (Röhle 1995).

Evaluation criteria

To engage in differentiated discussions on all transformation scenarios (Table 2) five criteria (forest growth, economics, carbon sequestration, stand stability and biodiversity) were defined. The results of each silvicultural scenario and

criterion were displayed scaled (best: 1, worst: 0; Koschke et al. 2012; Knoke et al. 2014). Each criterion was, in turn, made up of different factors (see Table 3). The efficiency of each scenario was quantified by summing the score of each of the studied criteria. To provide a measure of stability between the categories, the standard deviation (SD) for each forest transformation scenario was also determined.

Forest growth

The criterion forest growth consisted of the factor's total productivity, mortality over the entire simulation period and the standard deviation of tree heights as a proxy for a shelter in the event of a disturbance. If the overstorey is lost to disturbances, the understory can immediately utilise the increasingly available resources such as light, water and nutrients and take over important forest functions. In order to include the temporal component, the time since simulation start was classified into five classes (25 ± 10, 50 ± 10, 75 ± 10, 100 ± 10 and 125 ± 10 years), and averages of each class were obtained. Each of the five values was included in the evaluation without weighting.

Economics

The harvested trees were graded after each simulation period with the help of SorSim (Lemm et al. 2013) without the dead wood fraction. The revenues were calculated using averaged timber prices provided by the Bavarian State Institute of Forestry (LWF) for 2010–2015. Harvesting costs were calculated at 48 € m^{-3}, planting costs at 6400 € ha^{-1} for beech, 1600 € ha^{-1} for spruce and 2700 € ha^{-1} for fir. The net present value (NPV) was calculated using three different discount rates: 1%, 2% and 3%. The presented results included the financial value of the standing timber at the end of the simulation period.

Carbon sequestration

In order to calculate the stored in situ carbon quantities of the simulation results, both the above-ground biomass, using species-specific biomass formulae (Pretzsch et al. 2014), as

Table 3 Overview of the categories defined for the comparison of the different forest transformation scenarios and their factors

Forest growth	Economics (net present value) (%)	Carbon sequestration	Stability	Biodiversity (number of species)
Total productivity	1	In situ + ex situ in wood products + substitutions of fossil fuels	Survival probability of spruce * potential damaged timber	Flora
Mortality	2			Fauna
Standard deviation of tree heights	3		Spruce proportion in the last simulation period	Fungi

Each factor was included in the evaluation of the respective category without weighting

well as the underground biomass, with a root factor (root/shoot) according to Offenthaler and Hochbichler (2006), were estimated. The ex situ carbon content in wood products and the substitution quantities resulting from bioenergy use (wood combustion) were calculated using a harvested wood products (HWP) model from Klein et al. (2013). In presenting the C sequestration potential of forest management on a per hectare basis, we used the levelisation approach, where the periodic C flows were summed up and discounted with an assumed social interest rate of 2% (e.g. Hoen and Solberg 1994).

Biodiversity

The number of species of (1) flora, (2) fauna and (3) fungi were selected as indicators for a non-wood forest function. In order to determine the number of species of flora, fauna and fungi, each of the 30 stands was divided into 1000-m² grids. According to Zenner et al. (2016), each raster was then assigned to one of nine forest successional stages (gap, regeneration, establishment, early optimum, mid-optimum, late optimum, plenter, terminal and decay). Finally, based on the results of Hilmers et al. (2018), the number of species of flora (higher plants, lichen and mosses), fauna (phytophagous and pollinating arthropods, vertebrates and invertebrates feeding on animal tissue, species feeding on dead tissue and species depending on dead wood during their life cycle) and fungi was able to be assigned to the individual forest successional stages. The species numbers of the entire 2-ha plots consisted of the average of all 1000 m² large squares. Standard deviations were also calculated again using the average of each of the five classes since simualtion start (see above).

Stability

The calculations of the stability of the stand against natural disturbances were calculated on the basis of a model developed by Roessiger et al. (2013). In a mixed stand, the survival probability of the spruce was calculated by means of a Weibull function (Weibull 1951) depending on the percentage of spruce and age. The probabilities of beech and fir survival were assumed to be independent of the percentage of spruce (Roessiger et al. 2013). Using the five classes since simulation start (see above), the survival probabilities were calculated at different simulation points in time. These survival probabilities were then multiplied by the potential amount of damaged wood volume (all spruce trees higher than 66% of the mean height of the 100 thickest spruce trees). They were then included in the valuation as separate factors without weighting. Assuming that stable stands at the end of the simulation could either appear due to the young

age of the spruce, or due to a low proportion of spruce, the share of spruce of the total stand in the last simulation period was used as an additional factor. Since those stands with a high proportion of spruce and young age will become unstable again in the future, those stands with a lower proportion of spruce were rated as better.

Results

Apart from the strip clear-cut and the do-nothing scenario, all the methods were successful for transformation into semi-natural mixed forests at equilibrium. Although natural regeneration of beech and fir was always present in the strip clear-cut scenario, spruce dominated the advanced development phases of the stands. In the do-nothing scenario, no or very little natural regeneration occurred. Differences between the shelterwood, slit and gap scenarios are shown in terms of their specific criteria.

Validation of the simulation results

Figure 1 shows the periodic annual increment versus the volume of the remaining stand in each simulation period. The results of the do-nothing scenario showed that long-term experimental plots made of pure spruce showed higher growth rates at the same volumes of the remaining stand
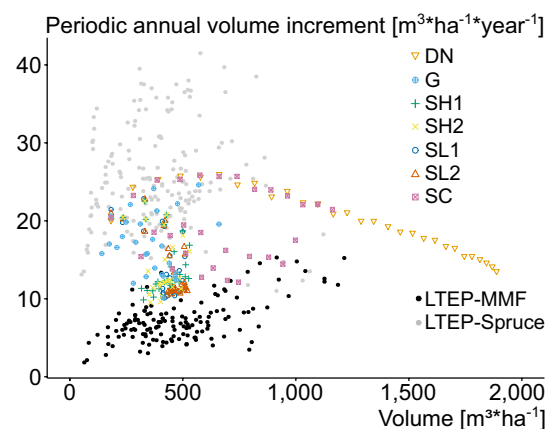

Fig. 1 Relationship between stand periodic annual volume increment and volume of the remaining stand. Black dots show the results from long-term experimental plots consisting of pure spruce (LTEP-Spruce); grey dots show the results from long-term experimental plots consisting of spruce, fir and beech (LTEP-MMF). Other symbols show the simulation results of various forest transformation scenarios. DN, do-nothing scenario; G, gap-coupes with planting of beech and fir; SH1, shelterwood-coupes with natural regeneration; SH2, shelterwood-coupes with planting of fir and beech; SL1, slit-coupes with natural regeneration; SL2, slit-coupes with planting of fir and beech; SC, strip clear-cutting with natural regeneration. See Table 2 for a detailed description of the different scenarios. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article

than experimental plots from the mixed mountain forest zone (beech, spruce and fir). The results from the simulations for all scenarios were lying between the results of the long-term experimental plots.
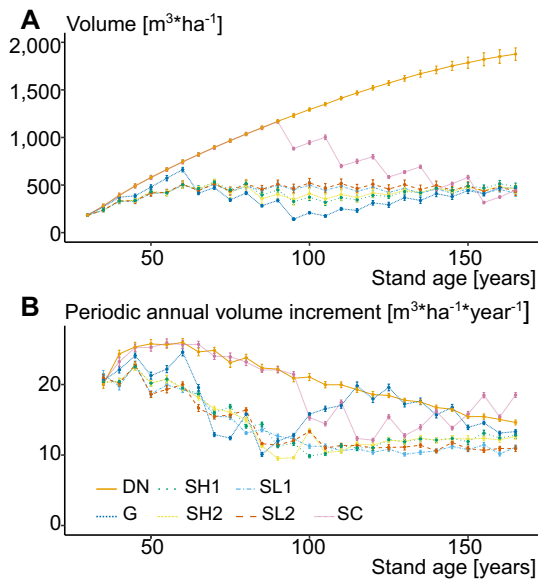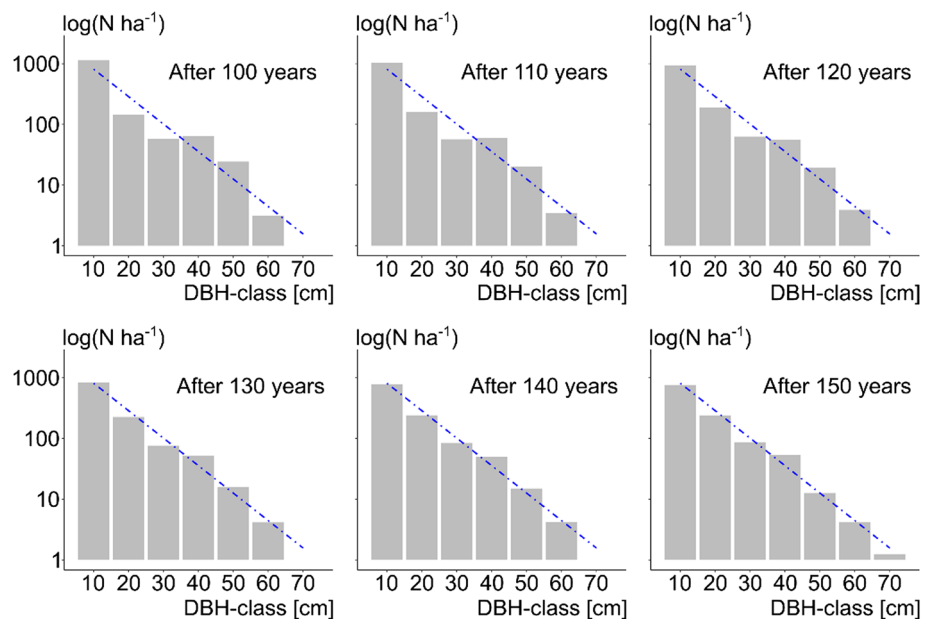

Fig. 2 Volume of the remaining stand in m³ ha⁻¹ (**a**) and stand periodic annual volume increment in m³ ha⁻¹ year⁻¹ (**b**) with standard errors, resulting from different tree growth between 30 simulations, above stand age of all the simulated transformation scenarios. DN, do-nothing scenario; G, gap-coupes with planting of beech and fir; SH1, shelterwood-coupes with natural regeneration; SH2, shelterwood-coupes with planting of fir and beech; SL1, slit-coupes with natural regeneration; SL2, slit-coupes with planting of fir and beech; SC, strip clear-cutting with natural regeneration. See Table 2 for a detailed description of the different scenarios. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article

Forest growth

The stand periodic annual volume increment (PAIV) of the slit and shelterwood scenarios stabilised from a stand age of around 80 years to a value of approx. 10 m³ ha⁻¹ year⁻¹ and formed a steady state until the end of the simulation (Fig. 2). Volume of the remaining stand in the slit and shelterwood scenarios quickly leveled out between 400 and 500 m³ ha⁻¹. Figure 3 shows how the slit scenario approaches a possible steady-state curve in the simulation run after 150 years. It is striking how the 'gap' in the diameter frequency distribution between 20 and 30 cm, still visible after 110 years of simulation, was filled after 130 years of simulation.

However, due to higher stand densities, the PAIV of the do-nothing scenario was higher than for all other scenarios over the entire simulation period (Fig. 2). In the case of standing volume and PAIV, the strip clear-cut scenario was similar to that of the do-nothing scenario up to the time of the first treatment. The gap scenario also showed the greatest fluctuations in terms of PAIV, similar to the standing volume.

Economics

In terms of economics, the results were similar for most management scenarios. Just the results of the do-nothing and the strip clear-cut scenario differed from the others (Figs. 4, S1). The do-nothing scenario showed, due to the potential liquidation value of the portfolio at the end of the simulation period, comparable net present values only in the calculation of the net present values with a 1% discount rate. As the discount rate increased, the net present value dropped sharply and was significantly smaller than in the other scenarios.
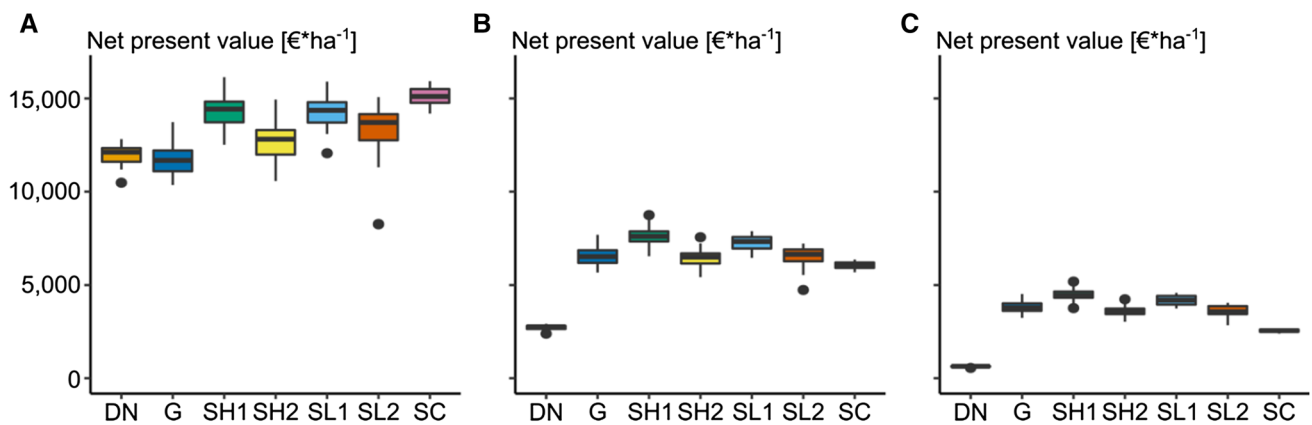

Fig. 3 Stem distribution (N/ha for DBH-classes) of the slit-coupe scenario with planting of fir and beech after 100, 110, 120, 130 and 150 years of simulation. The curve corresponds to a steady-state condition for uneven-aged stands of spruce, which could be reached in the long run (Prodan 1944). Note that the number of trees per hectare and DBH-classes was log transformed

Fig. 4 Boxplots of the net present values of the different transformation scenarios. The net present value is calculated using three different interest rates: 1% (**a**), 2% (**b**) and 3% (**c**). The presented results include the potential liquidation value of the portfolio at the end of the simulation period. DN, do-nothing scenario; G, gap-coupes with planting of beech and fir; SH1, shelterwood-coupes with natural regeneration; SH2, shelterwood-coupes with planting of fir and beech; SL1, slit-coupes with natural regeneration; SL2, slit-coupes with planting of fir and beech; SC, strip clear-cutting with natural regeneration. See Table 2 for a detailed description of the different scenarios

Table 4 Mean C sequestration (tC ha^{-1}) according to the levelisation approach in the different scenarios over 150 years

Scenario	In-situ	Wood products	Substitution	Total
DN	171.5	0.0	0.0	171.5
G	47.5	30.9	321.5	399.9
SH1	47.8	27.6	258.9	334.4
SH2	48.4	26.8	249.1	324.3
SL1	49.1	26.7	262.1	337.9
SSL2	52.4	25.3	247.7	325.4
SC	110.9	15.8	275.3	401.9

See Table 2 for abbreviations and a detailed description of the different scenarios

A very similar pattern can be observed in the strip clearcut scenario. Even if it was still the best variant in the calculation with a discount rate of 1%, it fell behind the slit, shelterwood and gap variants in the calculation with higher discount rates. The slit, shelterwood and gap variants only differed in the planting costs of beech and fir and otherwise showed very similar results. However, the planting costs had a very strong impact on the net present values.

Carbon sequestration

Table 4 shows the mean carbon sequestration of the seven transformation scenarios, as well as the in situ storage, the carbon storage in wood products and the substitution of fossil fuels. The do-nothing scenario showed the highest in situ storage. Due to the lack of intervention, however, no carbon was stored in wood products or achieved by substituting fossil fuels. Overall, the do-nothing variant was, therefore, the one with the lowest carbon sequestrate values. Highest values were achieved by the strip clear-cut and gap scenarios. While the strip clear-cut scenario showed high in situ carbon storage values, the gap variant had higher values in the areas of wood products and substitution of fossil fuels. The shelterwood and slit scenarios showed similar values with slightly higher values in the scenarios with natural regeneration. Overall, our results showed that the substitutions of fossil fuels were the most important factor to consider when looking at total carbon sequestration.

Stability

In terms of stability, we found the highest potential damages of spruce caused by disturbances in the do-nothing scenario (Fig. 5). Survival probabilities decreased with age. As we found the highest values of volume of the remaining stand, the potential damaged wood volume was also the highest for this scenario. For the other scenarios, the survival probabilities decreased for the first 100 years of simulations and then after increased. The proportion of spruce was 100% in the do-nothing and the strip clear-cut scenario at the end of the simulation runs. In case of slit and shelterwood, the proportions of spruce at the end of the simulations were higher in the scenarios with natural regeneration, than in the ones with plantings of beech and fir. Although beech and fir were planted in the gap scenario, the proportion of spruce at the end was still high (75%).

Biodiversity

For all three kingdoms (flora, fauna and fungi), considerable changes in the potential number of species were observed
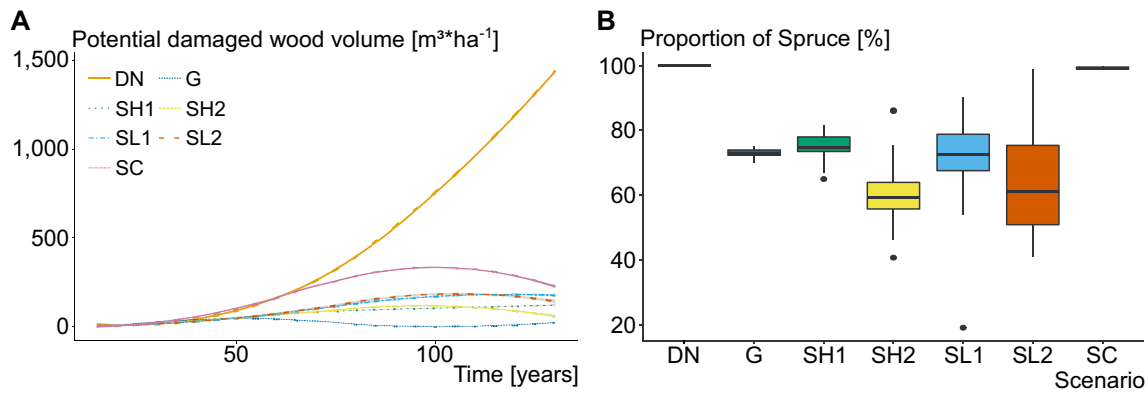
Fig. 5 Relationship between the potential damaged wood volume and the time since simulation start of all simulated scenarios (**a**) and the proportion of spruce in the last simulation period (**b**). Lines were generated by fitting a loess curve. DN, do-nothing scenario; G, gap-coupes with planting of beech and fir; SH1, shelterwood-coupes with natural regeneration; SH2, shelterwood-coupes with planting of fir and beech; SL1, slit-coupes with natural regeneration; SL2, slit-coupes with planting of fir and beech; SC, strip clear-cutting with natural regeneration. See Table 2 for a detailed description of the different scenarios. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article

over the simulation runs (Fig. 6). Vascular plants are directly dependent on sunlight reaching the forest floor. In the do-nothing scenario, little natural regeneration has occurred and mortality has opened the canopy over time. Thus, more sunlight could reach the forest floor. Therefore, we found the highest numbers of vascular plants in the do-nothing scenario after 100 years of simulation (which means a stand age of > 140 years; Fig. 6a). We observed a similar trend in the strip clear-cut scenario. However, due to the natural regeneration, the canopy closed again after the silvicultural treatments and the number of vascular plants species decreased at the end of the simulation runs. Starting with the first silvicultural treatments, we found increasing numbers of vascular plants species during the first 50 years of simulation in the slit and shelterwood scenarios. After 70 years of simulation, the number of vascular plants species decreased due to increasing canopy density and outshading and was constant during the last 50 years of simulation. We found a similar pattern in the gap-coupes scenario. However, due to the strong silvicultural treatment towards the end of the simulation, the number of species increased again in this scenario.

As consumers depend on the primary producers, the number of species in the fauna kingdom showed very similar trends (Fig. 6b). The number of species rose sharply for a period in the slit, gap and shelterwood scenarios (open canopies), decreased afterwards and were constant at the end of the simulation runs. Again the number of species increased at the end of the simulation runs in the gap scenario. The do-nothing scenario showed a high number of species after 100 years of simulation.

Contrasting to the kingdoms of flora and fauna, the number of fungi species are following a bell-shaped pattern along forest succession. We found an increasing number of species of fungi in the do-nothing and strip clear-cut scenarios peaking at 50 years of simulation (Fig. 6c). While we found just a slight decrease in the number of species in the do-nothing scenario afterwards, the number of species decreased drastically in the strip clear-cut scenario due to starting silvicultural treatments. In the slit and shelterwood scenarios, the number of species was lower during the first 70 years of simulation. However, as canopy density increased the number of fungi species was highest in these scenarios during the last 80 years of simulation. A different pattern was found in the gap-coupes scenario. In this scenario, the number of species was lowest during the first 70 years of simulation, increased afterwards with a peak at 130 years of simulation and slightly decreased at the end of the simulation runs.

Evaluation with multiple criteria

Figure 7 shows the results of the overall evaluation with regard to the individual scenarios concepts. The do-nothing scenario showed the best biodiversity performance and ranked last for the other four criteria. The slit scenario with natural regeneration, slit with planting and the gap scenario showed balanced results in all categories. The results of the shelterwood scenario with natural regeneration, shelterwood with planting and the strip clear-cut scenario showed divergent results between the criteria. In order to illustrate the divergence of all the criteria within a silvicultural scenario, the standard deviation of each scenario between the categories was calculated (Fig. 8). This
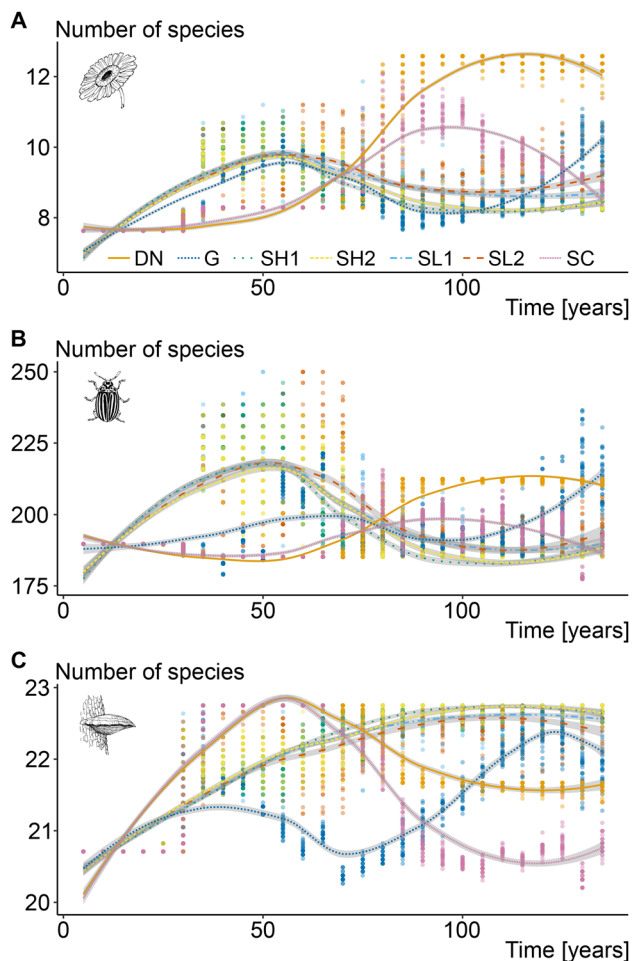
Fig. 6 Trends in the number of species of flora (**a**), fauna (**b**) and fungi (**c**) for time since simulation start of all the simulated scenarios. Lines were generated by fitting a loess curve. Grey areas represent the 95% confidence interval. DN, do-nothing scenario; G, gap-coupes with planting of beech and fir; SH1, shelterwood-coupes with natural regeneration; SH2, shelterwood-coupes with planting of fir and beech; SL1, slit-coupes with natural regeneration; SL2, slit-coupes with planting of fir and beech; SC, strip clear-cutting with natural regeneration. See Table 2 for a detailed description of the different scenarios. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article

approach enables a direct comparison of the individual silvicultural scenarios based on the total score. Scenarios, such as the slit scenarios with a high total score and small standard deviations between the scores, can be described as stable. The shelterwood scenarios show a relatively high total score, but at the expense of a higher standard deviation.

Discussion

It was shown that it might be possible to transform secondary pure spruce stands to stable mixed mountain forests with five of the seven scenarios (H1). It is also these five scenarios (gap, shelterwood, slit) which are expected to maintain these structures in the long term with regular forest interventions (H2). The evaluation of multiple criteria allows the seven scenarios to be divided into three groups. The do-nothing scenario only achieved the highest score in the category of biodiversity. The shelterwood and strip clear-cut scenarios showed highly divergent scores, while the slit and gap scenarios achieved high scores in all categories (H3).

While the management scenarios studied here mimic current management recommendations (Mosandl 1984; Streit et al. 2009; Bayerische Staatsforsten AöR 2018) in a highly realistic manner, it was applied uniformly across all the simulation runs. This approach disregards the potential adaptive measures of managers (Yousefpour et al. 2017), which are increasingly likely as climate change impacts worsen (Blennow et al. 2012; Seidl et al. 2016). Furthermore, it is unrealistic to presume constant site and climatic conditions for the next 150 years, as chosen in the present investigation. The simulation of a site-condition drift is, in principle, possible with the used growth model by changing the height or diameter-growth potential over time. For our simulation runs, where the central goal was the comparison of distinctly different treatment strategies, we assumed steady-state climatic and site conditions (Hanewinkel and Pretzsch 2000).

Despite these limitations, one of the backbones of this study is the reliability of the model SILVA in terms of providing the realistic quantitative results in terms of tree and stand growth. The model is used for applications in practice since the late 1990s, and the current version has been quantitatively calibrated with about 350,000 single-tree growth observations from long-term research plots (Pretzsch 2009, p. 519). Mixed mountain forests and pure spruce stands in Bavaria are particularly well represented in this data set. Thus, this study applied the model in a core area of its validity, which became also evident in the presented validation runs. The evaluation criterion *forest growth* was therefore directly covered by this validity. The other criteria (*economics*, *carbon sequestration*, *biodiversity*, *stability*), in contrast, were not primary simulation output variables, and they rather result from secondary calculations made on the former. However, the development of the standing stock and growth and the achievement of a long-term steady state play a crucial role, and most other criteria depend on this steady-state structure, volume and growth (Forest Europe 2011; MCPFE 1993; Dieler et al. 2017). All the methods applied and associated assumptions are documented and verified in published research works (see corresponding parts of the
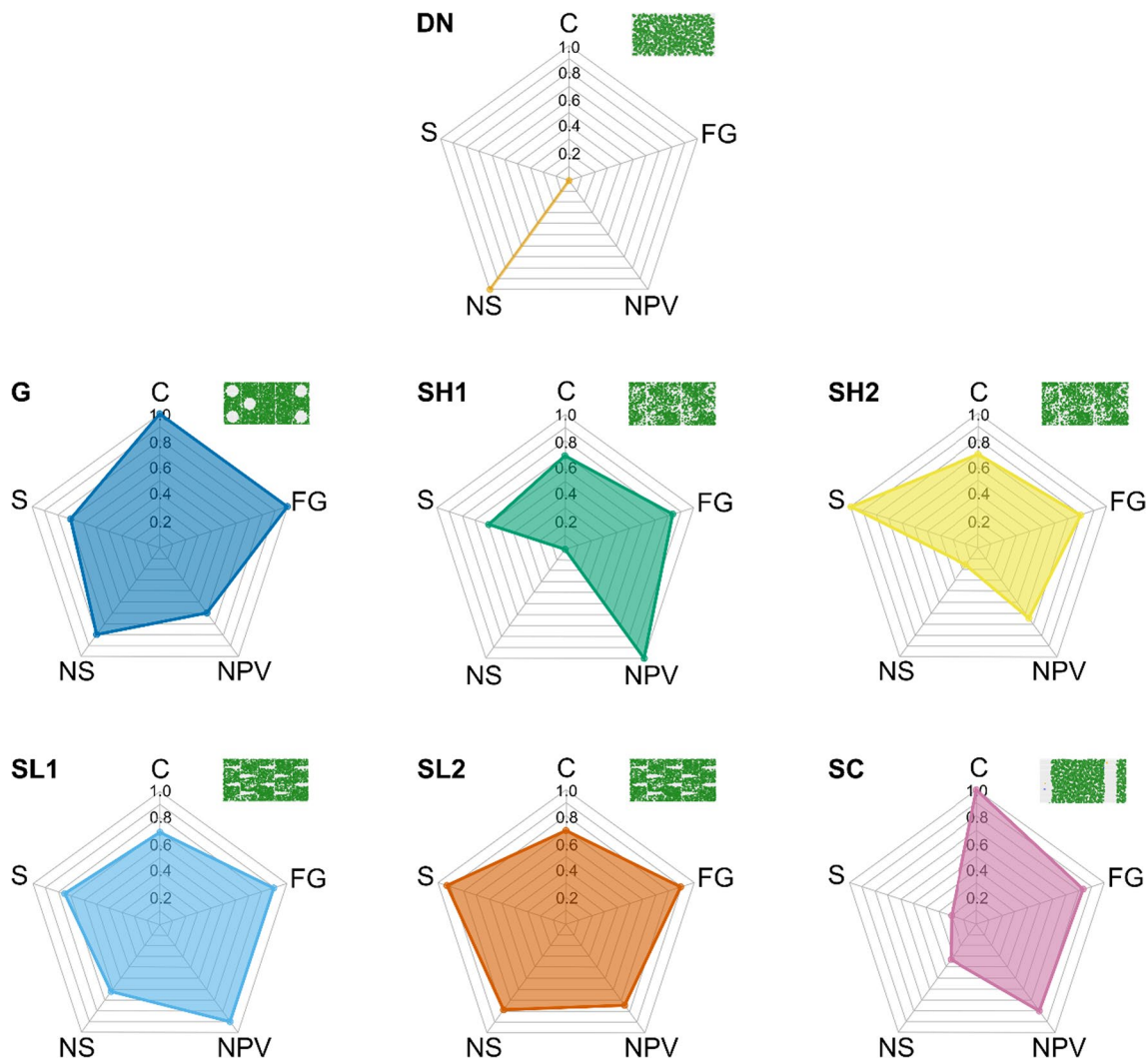
Fig. 7 Radar chart of the evaluation of multiple criteria. FG, forest growth; NPV, net present value; C, carbon sequestration; S, stability; NS, number of species. The scaled results of the respective factors of each criterion are shown (see Table 3 for explanation). The results were scaled between 0 and 1. The results evaluated with 1 represent the best scenario in comparison with the other scenarios. Categories rated 0 show the worst scenario. DN, do-nothing scenario; G, gap-coupes with planting of beech and fir; SH1, shelterwood-coupes with natural regeneration; SH2, shelterwood-coupes with planting of fir and beech; SL1, slit-coupes with natural regeneration; SL2, slit-coupes with planting of fir and beech; SC, strip clear-cutting with natural regeneration. See Table 2 for a detailed description of the different scenarios

methods section). So, we feel, our simulation and evaluation methodology—with a valid growth and yield model at its fundament—can be meaningfully applied given the goals of this study.

Forest transformation

The newly introduced species (beech and fir) can be established by planting or natural regeneration after artificial disturbances such as shelterwood, slit or gap-coupes. In their study on the transformation of even-aged to uneven-aged stands of spruce, Hanewinkel and Pretzsch (2000) showed that a transformation is strongly dependent on the gap size.

They showed that regeneration can only be established from gap sizes larger than 40 m in diameter. However, this study only includes the regeneration of spruce. Our study demonstrates that smaller gap sizes are sufficient if shade tolerant species are involved in the transformation process by planting or from natural regeneration if potential mast trees are located nearby. The smaller interventions also have less impact on the periodic annual volume increment at the stand level. This is in line with Brunner et al. (2006) who demonstrated, based on silvicultural scenario modelling, a transformation of spruce stands by under-planting with beech in a gradually opened stand of spruce.
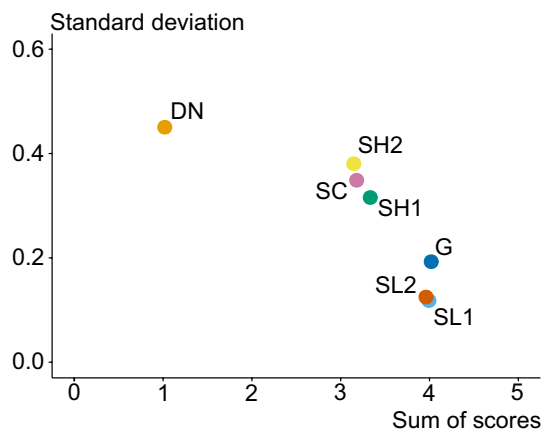
Fig. 8 Standard deviation of the scores from the five criteria (forest growth, economics, carbon sequestration, (stand) stability and biodiversity) over the sum of the scores. DN, do-nothing scenario; G, gap-coupes with planting of beech and fir; SH1, shelterwood-coupes with natural regeneration; SH2, shelterwood-coupes with planting of fir and beech; SL1, slit-coupes with natural regeneration; SL2, slit-coupes with planting of fir and beech; SC, strip clear-cutting with natural regeneration. See Table 2 for a detailed description of the different scenarios and Table 3 for an overview of the five criteria

In the strip clear-cut scenario, after the removal of all the trees from the strip, natural regeneration of beech and fir started (if potential mast trees are located nearby). However, beech and fir were outcompeted by spruce later on. This may be avoided by earlier planting or groupwise separation of the three species, for example, through pre-commercial thinning (Brunner et al. 2006). Regulation of the mixture could be accomplished in SILVA only by thinning crop trees at a very early age. However, in the long run, the small-scale interventions of the slit-coupe scenarios might better support asynchronous forest dynamics than the other scenarios and thus support the forest's inherent adaptive mechanisms (Morin et al. 2014). In the do-nothing scenario, spruce remained dominant until the end of the simulation and the regeneration of fir and beech appeared only slowly. Suggestions by e.g. Drever et al. (2006) that unmanaged development might enable natural processes to restore the original species composition of the forests cannot be supported by our study, at least not in the time span of the simulation period. The slow rate of tree species change agrees with Schelhaas et al. (2015), who suggested that European forests are very inert and that altering their species composition requires a long time. The simulation results of Hlásny et al. (2017) in the Goat Backs mountain area of Slovakia also confirm these results. However, larger natural disturbances are to be expected in mountainous forests (Bircher et al. 2016), and the partial accumulation of the natural regeneration of non-spruce species is realistic (Buma and Wessman 2013). In all presented scenarios, climate change

and disturbance-mediated support to tree species diversity should be considered as an opportunity for forest adaptation efforts in spruce-dominated stands. Indeed, adverse effects, such as productivity losses or bark beetle outbreaks, must not be marginalised (Jönsson et al. 2007; Fleischer et al. 2016; Hlásny et al. 2017).

The lower stand periodic annual volume increment of long-term experimental plots has to be put into perspective to the extent that the proportion of spruce in the simulation plots was higher, and disturbing events, such as wind and bark beetle infestation, cannot be adequately represented by SILVA. As damage was not modelled in our scenarios, the standing volume of the remaining stand in the do-nothing scenario reached values of almost 2000 m^3 ha^{-1} only occasionally found on experimental plots. The comparative results from untreated long-term experimental plots with pure spruce show maximum volumes of the remaining stand of approx. 1600 m^3 ha^{-1} (Röhle 1995). We accepted this bias in the results as all the scenarios were flawed in the same way. We were interested in the relative differences and ranking of the scenarios, rather than in their absolute performance.

In order to transform the destabilised pure spruce forests into stable mixed mountain forests on a large scale, methods should be found to reduce the high harvest costs (Valente et al. 2014; Jandl et al. 2018). For example, Valente et al. (2011) demonstrate that a whole-tree system employed in alpine conditions showed lower costs and emissions and therefore offered greater economic and environmental benefits than the traditional shortwood system. Furthermore, the same authors showed that cable yarding seems to be very efficient in terms of having a minimal impact on residual stand and soil which seems particularly important against the background of already destabilised forests.

Long-term safeguarding of forest transformation

Although the slit and shelterwood scenarios reached steady-state conditions at the last 50 years of the simulation runs, these structures can only be artificially maintained in their characteristic structures by continuous removal in the upper and middle layers. Without silvicultural interventions over a longer period of time, the upper and middle layers may become so dense that the regeneration layer no longer receives enough light, precipitates and the balanced age structure is lost (Pretzsch 2019). Anyway, as long as there are continuous silvicultural interventions, tree species compositions will remain stable due to the slit and shelterwood scenarios and will ensure the desired forest redevelopment in the long term. The gap scenario also suggests that the transformation will be successful in the long term. Although this scenario is, due to the higher amounts of harvested wood, less stable in terms of stand periodic annual

volume increment over the entire simulation period, this scenario achieves a higher tree species mixture and an uneven-aged structure at the end of the simulation runs. In terms of productivity, these mixed uneven-aged stands have the advantage of being more productive compared to neighbouring pure stands (Pretzsch et al. 2015) on the one hand, and, on the other hand, that a potential reduction in the volume increment of one species can be compensated for by higher volume increments of another species (Hilmers et al. 2019).

Evaluation of multiple criteria

The evaluation of multiple criteria allowed to highlight three basic patterns: The shelterwood and strip clear-cut scenarios showed highly divergent scores, while the slit and gap scenarios achieved high scores in all categories. The do-nothing scenario only achieved the highest score in the category of biodiversity. However, as unmanaged forests are increasingly valued for their benefits in the context of biodiversity conservation (Paillet et al. 2010), an increasing share in the landscape will not necessarily lead to a reduction in important regulating ecosystem services. For example, Seidl et al. (2019) showed that, in a mountain forest landscape, the regulation of both climate and erosion was higher in unmanaged systems, compared to systems implementing current management recommendations (see also Irauschek et al. 2017; Mina et al. 2017; Langner et al. 2017). It is important to note, however, that many rural mountain communities not only depend on regulating ecosystem services, but also generate a substantial part of their income and livelihood from managing natural resources (Häyhä et al. 2015). Not managing forests might thus negatively affect rural communities and result in the loss of other important ecosystem services, such as the supply of timber and biomass for bioenergy.

Although the evaluation of multiple criteria presented here is innovative for a holistic view of silvicultural concepts, the entire forest complex should not be reduced to the criteria described here. Furthermore, the considered indicators are only proxies for the respective services and differ with regard to how closely they resemble the relevant underlying processes. However, based on the available results, the determinant effects of the different silvicultural concepts could be made visible, even for those who have not yet been able to draw on empirical studies or practical experience because of the new concepts. It was the aim of this study to develop and evaluate a set of technically feasible management options for the transformation to semi-natural mountain forests; the choice of the optimum or best scenario also depends on economic, social, legal and eco-political factors not covered by this study.

Significance for forest transformation worldwide

Forestry has been changing throughout its history in response to the changing needs of human populations and changing supplies of forest resources and values to satisfy these needs (Kimmins and Blanco 2011). Worldwide, there is a multitude of forests which have been destabilised during history. For example, the forests in Bangladesh or the temperate rainforests in Canada and the USA face similar challenges to the destabilised forests in the Alps of Europe resulting from the former salt works supply. They are to be transformed to sustainable, stable but managed systems. Our results show that there are several equivalent trajectories to achieve these goals. Thus, the risk of failure if one does not strictly follow a sophisticated guideline is low. There is little reason, therefore, why transformation of destabilised forest should not be attempted in order to suffer fewer human casualties and economic damage in the future, in many regions of the world.

Conclusion

Silvicultural scenario comparisons quantify the long-lasting impact of management decisions on the stand and landscape (Niedertscheider et al. 2017; Thom et al. 2018); they can reveal how current decisions influence the future management options and flexibility to react to environmental changes. The results of the presented study showed that continuous forest interventions can transform secondary spruce stands into mixed mountain forests which are in a steady state in terms of stem diameter and tree species distribution. Of the investigated scenarios, we consider the ones with gaps or slit cuts to have the most beneficial overall utility values for the portfolio of five evaluation criteria. If timber production is not a management goal, and the focus is on nature conservation, the do-nothing regimes turned out to be a possible solution. However, it was not the aim of this study to present the 'best' management regime in mountain forests, but to exemplify and demonstrate the evaluation of management options with regard to related trade-offs between evaluation criteria.

Given that mountain forest management is highly cost and labour intensive (Valente et al. 2014; Jandl et al. 2018), spatially explicit simulation models can help to evaluate silvicultural practices which have not yet been sufficiently tested in practice, even if they may not be able to reproduce future developments in detail. However, with our results, we have showed that it is possible, by means of several trajectories, to return destabilised forests to sustainable, stable but managed systems. They showed that a transformation is realistic, even if sophisticated silvicultural concepts are

not strictly pursued. In order to suffer fewer human casualties and less economic damage in the future, transformation efforts of destabilised forests should therefore be pursued worldwide.

Compliance with ethical standards

Conflict of interest The authors declared that they have no conflict of interest.

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