



Simulating conversion of even-aged Norway spruce into uneven-aged mixed forest: effects of different scenarios on production, economy and heterogeneity

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Abstract

Despite a general lack of knowledge on the effects of different strategies, conversion of even-aged stands to uneven-aged forest is ongoing across Europe. Conversion of Bavarian Norway spruce stands under the present climate scenario was simulated using the individual tree simulator SILVA. Three conversion strategies initiated at two different stand ages, 30 and 60 years, were simulated to develop uneven-aged mixed stands of Norway spruce, silver fir and European beech: gap creation, shelterwood and passive conversion. The three conversion strategies were furthermore combined with different harvesting rates. These conversion scenarios were compared with maintaining the even-aged Norway spruce management as reference. Scenarios were evaluated in terms of mean annual increment and structural development over a 150-year conversion period as well as the expectation value (EV) for eternal future rotations. Compared to the reference scenario, conversion scenarios reduced mean annual increment (6–43%) and also generally EV (–5–78%), except for some scenarios when stand age at conversion was 60 and applying a 3% discount rate. Conversion by shelterwood always reduced EV (both compared to the reference and other conversion scenarios) when initiated at age 30. With passive conversion, the effect on EV was dependent on the assumptions regarding regeneration costs. Gap conversion generally resulted in high EV and increased stand heterogeneity fastest among the different strategies. Other scenarios, especially passive conversion, were dependent on heavy thinning for developing heterogeneity faster (although still slower than with creation of gaps). Most conversion scenarios eventually resulted in similar structural heterogeneity, but the time it took to get to this stage varied greatly (50–120 years). Conversion by creation of smaller gaps in combination with a high rate of target diameter harvesting resulted in a favorable conversion in terms of economic returns and development of stand heterogeneity due to early income and differentiated regeneration.

Keywords Transformation · Near-natural forest · Selection forest · Structure · Beech · Silver fir

Introduction

In many regions of Europe, mono-specific and even-aged plantations are converted to uneven-aged forest because of anticipated benefits of uneven-aged forest systems with regard to, e.g., biodiversity protection (Hekhuis and Wieman 1999; Larsen 2012; Pretzsch 1998) and reduced risk of damage to the forest ecosystem, e.g., from wind throw (Pukkala et al. 2016). Conversion of pure Norway spruce (*Picea abies*) is a particular priority as 6–7 million ha have been planted with this species outside of its natural distribution in Europe (Brunner et al. 2006; Hanewinkel 2001; von Teuffel et al. 2004). Consequently, these Norway spruce stands are often vulnerable to damage from natural hazards, such as wind throw (Schütz et al. 2006), bark beetles (Christiansen and Bakke 1988) and root rot (Delatour 1998; Ronnberg

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et al. 1999). Furthermore, Norway spruce is predicted to have a poor resilience towards the future climate (Huang et al. 2017). As a consequence, it is estimated that at least 4–5 million ha of Norway spruce will have to be converted in the long run (von Teuffel et al. 2004).

Although not a novel concept, conversion of mono-specific, even-aged stands to uneven-aged, mixed forests is new to many regions of Europe (Vítková and Dhuháin 2013). Knowledge on adequate strategies for the conversion into uneven-aged forest as well as the results in terms of wood production, economic outcome and forest structure is therefore limited. Studies conducted so far mainly focused on the earlier steps in the conversion, while the longer time span has largely been omitted (Vítková and Dhuháin 2013). Different stand conditions make it complicated to give general recommendations and have, along with the long time span involved in the conversion, been an important reason why so few experimental plots on conversion have been established (Kenk and Guehne 2001). Those few plots that do exist have not yet been sufficiently long under observation to provide sufficient evidence on the consequences of conversion in terms of production, economic output and structural heterogeneity.

Some knowledge on conversion processes is, however, available, especially from Central Europe (von Lüpke et al. 2004), which has been formulated in a few regional guidelines for the conversion of plantations to uneven-aged forests (e.g., Bayerische Staatsforsten AöR 2018; Larsen and Skov- og Naturstyrelsen 2005). The guidelines cover both passive as well as active conversion methods. Active conversion refers to the active removal of large volumes in the overstorey, before the trees reach the target diameter (TD), to benefit regeneration. Passive conversion is likely to provide a better economic result but is also expected to result in slower conversion (Larsen and Skov- og Naturstyrelsen 2005). However, the guidelines are largely based on theoretical schemes that have not been tested scientifically because there are hardly any practical examples for conversion (Hilmers et al. 2020). Thus, there is a need for scientifically validated schemes that can aid decision making of practitioners.

Because only little, and mostly short term, data are available and since conversion is a long-term process, consequences of conversion at present can mainly be assessed through modelling or analysis of chronosequences producing artificial time series (Pretzsch 2009). Such conversion modelling can be done in two different ways. The first option is to optimize conversion for a variety of parameters (e.g., Messerer et al. 2017; Roessiger et al. 2011, 2013; Yousefpour and Hanewinkel 2009). While this approach may provide a set of beneficial conversion schemes, the exploration of the trade-offs between different alternatives is less clear. Also, while distance-dependent individual tree simulators

could be used for optimization of the conversion to uneven-aged stands, no individual tree simulators in European forestry are to our knowledge capable of this at present. The second option is to define specific scenarios and investigate how these scenarios differ in the fulfillment of the management objectives, i.e., simulate how conversion will occur under a variety of conditions. While some studies have used a stand level approach, e.g., based on transition matrixes (e.g., Buongiorno 2001; Schou et al. 2012; Schou and Meilby 2013), a distance-dependent individual tree approach can incorporate spatial interactions among trees, which is important to produce realistic simulation of regeneration (Hyttiäinen & Haight 2012; Vanclay 2012). While, theoretically, distance-dependent individual tree simulators could be used for optimization of the conversion to uneven-aged stands, no available individual tree simulators in European forestry are to our knowledge at present capable of this (see Miina 1996 for optimization in an even-aged setting using individual tree distance-dependent model). Individual tree models have previously been used to simulate the conversion to uneven-aged forest in several studies using, e.g., the distance-independent Heureka (Drössler et al. 2015, 2014), BWINpro (Schröder et al. 2007) and the distance-dependent SILVA (Hanewinkel 2001; Hanewinkel and Pretzsch 2000; Knoke and Plusczyk 2001; Hilmers et al. 2020).

Due to its non-dependence on stand age, as well as its design for multi-criteria scenarios assessment, SILVA is well equipped for the simulation of uneven-aged stand development (Bravo et al. 2019). Since the early conversion studies in SILVA, the simulator has been equipped with a validated regeneration model (Biber and Herling 2002; Pretzsch et al. 2006) as well as calibrated with a large database on complex mixed uneven-aged stands (Hanewinkel and Pretzsch 2000). While Hanewinkel and Pretzsch (2000) looked at different conversion strategies and how these influenced the structural development, the study only did so for the simple case of converting even-aged Norway spruce to uneven-aged and did not include economic aspects. Hanewinkel (2001) and Knoke and Plusczyk (2001) both included an evaluation of the economic consequences of conversion, but they did not investigate different conversion strategies. In addition, no studies have so far quantified the effects of conducting conversion in stands of different age, which is an important factor for success in conversion (Mosandl and Küssner 1999; Schütz 2001). Finally, none of the aforementioned studies included a validation of the simulations with data from long-term mixed uneven-aged experimental plots. Such validation is important due to the complexity of modelling mixed uneven-aged stands (Bravo et al. 2019). Validation was undertaken in Hilmers et al. (2020), which simulated in SILVA the effect of different overall conversion strategies (e.g., using shelterwood and gaps). Hilmers et al. (2020) tested one stand age at conversion and different overall conversion strategies

were defined without varying factors such as target diameter harvesting (TDH) rate.

From the synthesis of studies assessing the conversion of even-aged Norway spruce into uneven-aged mixed forests, it follows that the consequences of different conversion methods are not sufficiently investigated for a variety of conditions. It is especially meaningful to simulate the conversion of pure Norway spruce stands to mixed uneven-aged forests of Norway spruce, silver fir (*Abies alba*) and European beech (*Fagus sylvatica*), hereafter referred to as spruce, fir and beech. This mixture is of special interest since it combines stability, also towards the predicted climate change (Albrecht et al. 2012; Hilmers et al. 2019; Vitasse et al. 2019), applicability in uneven-aged systems across Europe, and availability of data to validate simulations with (Pretzsch 2019; Pretzsch et al. 2015). Such validation data are available from experimental plots mainly located in the elevational zone of 600–1400 m known as the mixed mountain forest zone (Pretzsch et al. 2015). Furthermore, this mixture would allow keeping a significant percentage of fast growing, valuable conifers, which due to their favorable wood properties will likely continue to be in high future demand, e.g., for construction timber (Ramage et al. 2017; European Commission 2018).

In this study, we explored an array of conversion scenarios from even-aged spruce to uneven-aged forest of spruce, fir and beech. The aim was mainly to analyze and compare the consequences of different combinations of overall conversion strategy, thinning regime, TDH rate and stand age at conversion but also to compare these conversion scenarios to continued even-aged spruce management. Scenarios were compared in terms of stand productivity, economic performance and structural heterogeneity.

Methods

The conversion from even-aged spruce to uneven-aged spruce, beech and fir was simulated with synthetic stands of Norway spruce using the distance-dependent, individual tree simulator SILVA version 2.3 created by the chair of Forest Growth and Yield Science, the Technical University of Munich (Pretzsch et al. 2006). Firstly, we explain how we constructed the initial simulation stands and how we defined the growing conditions. Secondly, we explain the different conversion scenarios, and the reference Norway spruce scenario, we applied to these initial simulation stands. Thirdly, we show the methodology for validating the growth simulations for the conversion scenarios before lastly explaining the response variables used to compare different scenarios.

Table 1 Stand characteristics of the simulation stands at age 30 and 60 years. The stand variables were obtained from a local yield table (Assmann and Franz 1963) for site class 36 ($H_{100}=36$ m at index age 100). H_{100} =height of the 100 thickest trees ha^{-1} . D_g =quadratic mean diameter. N , tree number. G , basal area

	Stand age	
	30 years	60 years
H_{100} (m)	15.0	26.1
D_g (cm)	11.8	23.9
$N\text{ha}^{-1}$	2629	1067
G (m^2ha^{-1})	28.8	47.9

Construction of simulation stands

As basis for creating the synthetic spruce stands for the simulations, we used data from roughly 2,000 inventory plots (each 500 m^2) in the forest district Wasserburg am Inn (approximately 20,000 ha) in Bavaria, Germany. To assess local site quality, we extracted the average height of the five tallest trees (corresponding to the 100 highest trees ha^{-1}), which we used as a proxy for H_{100} (i.e., the average height of the 100 thickest trees ha^{-1}) and the stand age for each plot. Based on these roughly 2,000 data points, we performed quantile regression (90%) using the nonlinear Chapman–Richards function (with parameter estimates $A = 36.00$, $k = 0.035$ and $p = 2.034$) (Richards 1959) to derive a site index curve for a favorable site. This curve roughly fitted the height increment for site index 36 ($H_{100}=36$ m at index age 100) from the local yield table (Assmann and Franz 1963) and represents a common Bavarian site condition for spruce (Pretzsch 2002). Based on this local yield table, we obtained stem numbers (N), quadratic mean diameter (D_g), dominant height (H_{100}) and height corresponding to quadratic mean diameter (H_g) at stand ages 30 and 60 years (Table 1). These two stand ages represent different starting conditions for the conversion (Fig. 1).

Based on the stand variables in Table 1, we randomly created six synthetic spruce stands (three stands of age 30 and three stands of age 60) using the stand generator STRUGEN (a tool in the SILVA simulator, see Pretzsch 2002). Each of these six initial stands was subjected to all the treatments investigated in this study. This resulted in three replicates of each treatment, which incorporated the stochasticity from the different modules. This was especially important in regard to the modelling of mortality where the stochasticity can be problematic in individual tree models (Vanclay 2012). The created stands each had an area of $70\text{ m} \times 70\text{ m}$, but should be considered as part of a larger spruce forest with surroundings of similar characteristics. The simulated area of $70\text{ m} \times 70\text{ m}$ was a compromise between having enough space for executing silvicultural operations and processing time.

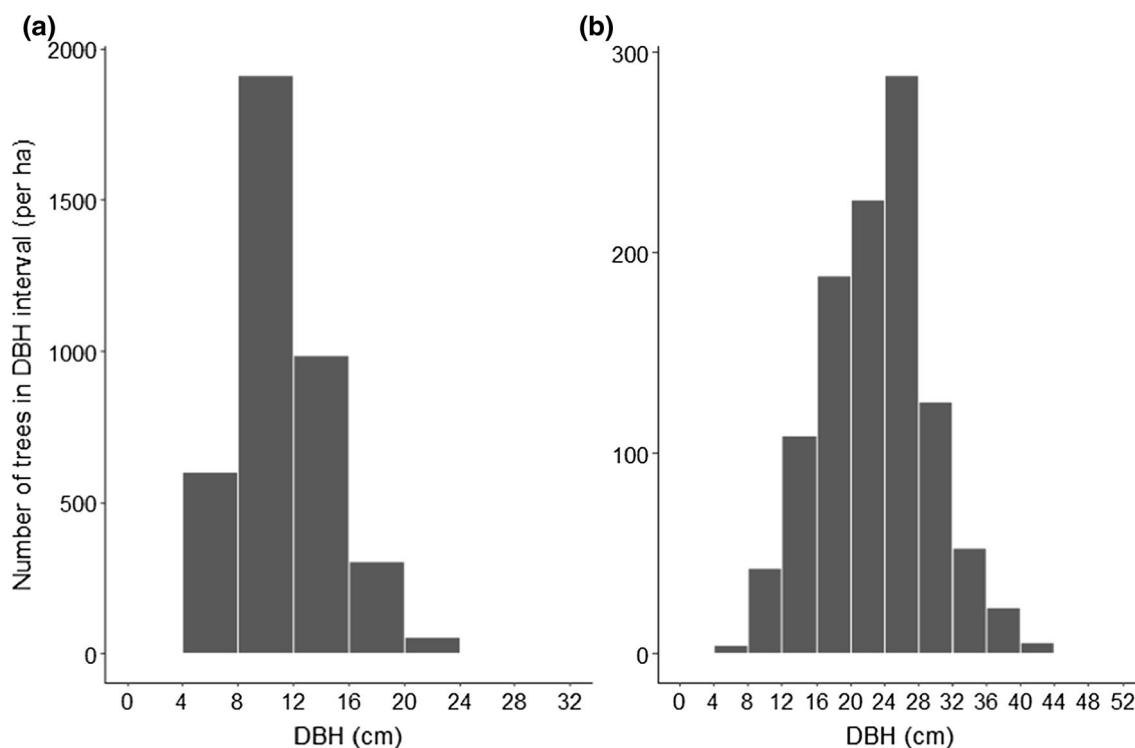


Fig. 1 Diameter distribution of the simulation stands at **a** age 30 **b** age 60

Specifying growing conditions

In SILVA, species-specific site quality is modelled from a number of site variables resulting in a site specific potential height growth curve. Consequently, we converted the observations of height growth (H_{100}) from Wasserburg am Inn, to potential height growth by multiplying with 1.138 (based on Kahn 1994). Then in SILVA, we manually chose the combination of site variables that most closely fitted this potential height growth curve. The resulting site specification was forest growth region “Isener Altmoräne und Hochterrasse”, at a latitude of 48°, an altitude of 525 m, soil moisture level of 6, soil nutrient level of 5, and no aspect or slope, a realistic site for a spruce plantations in the chosen forest district, especially Ebersberger Forst. Such sites typically have an average annual temperature of app. 7.5 °C, an annual precipitation of app. 900 mm and app. 500 mm of precipitation from May–September according to the 1960–1990 climatic norm that SILVA uses as standard.

After the site conditions were specified, the climatic parameters in SILVA were updated to a 2017 climate norm using the Global Climate model (AOGCMs) and emission scenario RCP 4.5 (IPCC 2013). Specifically, the update was conducted using ClimateEU v4.63 software, available at <http://tinyurl.com/ClimateEU> using methodology based on Wang et al. (2016). The result was an increase in temperature during May to September of 1.7 degrees and an

increase in the vegetation period of 18 days, relative to the 1960–1990 climate norm. This reduced site conditions for all species to site index 31 ($H_{100} = 31$ m at index age 100) (reduction was much more substantial for spruce).

Scenario setup

Unless mentioned otherwise, standard SILVA settings were used. Management was assigned on a 10-year basis for simplicity (see Table 6 in Appendix for an example on how simulations were carried out), although SILVA operates on 5-year time intervals. Harvesting is conducted in the beginning of a time period – before mortality and growth. Species composition in natural regeneration was modelled using the tree species share of basal area of adult trees, assuming that seed fall was proportional to the species share of basal area of adult trees. However subsequently, from seed fall to trees grew large enough to enter the growth model (> 7 m height), ecological differences in competition were incorporated (the shade-tolerant beech and fir were able to tolerate higher levels of competition than spruce). All natural regeneration was assumed to occur at no cost.

A simulation period of 150 years was used for assessing consequences of different conversion methods (hereafter named the conversion period). However, to ensure unambiguous economic comparison of alternative scenarios, we

Table 2 Programming the reference scenario in SILVA. N , tree number. V , standing stem volume. H_{100} , height of the 100 thickest trees ha^{-1} (m). D_{100} =quadratic mean diameter of the 100 thickest trees ha^{-1} (cm). Table layout adapted from Hanewinkel and Pretzsch (2000)

Procedure	Timing	Control parameters	Quantity and unit
Thinning for 300 future trees	Conducted once when $H_{100} = 11.5\text{--}14 \text{ m}^{\text{a}}$	Competitors removed per future tree	3–4 depending on $N_{\text{ha}^{-1}}$ before thinning
Thinning from above	$20 \text{ m} > H_{100} > 12 \text{ m}$	$N_{\text{ha}^{-1}}$ after thinning	App. 1400 trees· ha^{-1}
		$V_{\text{ha}^{-1}}$ thinned	Heavy thinning ^b
Thinning from below	$H_{100} > 20 \text{ m}$ and $D_{100} \leq 45 \text{ cm}$ and $N_{\text{ha}^{-1}} > 375$	$N_{\text{ha}^{-1}}$	Max 75 m^3
		$V_{\text{ha}^{-1}}$ thinned	Heavy thinning
Target diameter harvesting	When $D_{100} \geq 45 \text{ cm}$ is reached	Target diameter	Max 75 m^3^{c}
			1 st harvest: 45 cm
			2 nd harvest: 42 cm
		Harvesting rate	3 rd harvest: 0 cm
			100%

^aThe exception was that this thinning type was conducted for the first initial thinning at starting age 30

^bExamples of correlation between H_{100} and $N_{\text{ha}^{-1}}$ after thinning for heavy thinning (H_{100} , $N_{\text{ha}^{-1}}$): (20, 885) (30, 410)

^cThe exception to this limit was when the first thinning was performed in the highly stocked initial stands at age 60

employed an, in principle, eternal cash flow of the different management alternatives.

Reference scenarios

The reference scenario (maintaining pure spruce, hereafter referred to as Reference) for the different conversion strategies was simulated in accordance with the guideline for spruce management in Bavaria (BMFAF 1993). In short, the guideline is based on natural regeneration initiated at age 105 and gradual harvesting of the regenerated stand using a TDH criteria within a 20-year period. Reference was slightly altered compared to the guideline (Table 2) because following the guideline resulted in too many trees and a too long retention of the overstorey – likely due to the effect of climate change on spruce growth. In order to complete the harvest of the remaining trees within 20 years, the target diameter (TD) is reduced to 42 cm in the second harvest (10 years after TDH was initiated) and all remaining overstorey trees are removed after 20 years.

Conversion scenarios

Overall, three different conversion strategies were investigated in this study:

Passive conversion: A passive conversion using a combination of selective thinning and TDH

Shelterwood conversion: Using a combination of selective thinning and TDH, but

conversion is initiated actively with a very heavy, future tree oriented thinning reducing stand density to 300 and 100 trees ha^{-1} for stands converted at age 30 and 60, respectively

Gap conversion:

Using a combination of selective thinning and TDH, but conversion is also initiated actively by creating a 30 m diameter gap at 5, 25 and 45 years after conversion initiation. The gaps were installed in the stand with centers at these coordinates; (Gap 1: 18.3 m, 18.3 m), (Gap2: 51.67 m, 18.3 m) and (Gap3: 35.0 m, 51.7 m). Gap cutting were programmed in R (R Core Team 2017) and imported into SILVA

For the remainder of the study, these strategies are referred to as *Passive*, *Shelterwood* and *Gaps*. *Shelterwood* and *Gaps* are both examples of active conversion strategies.

Within these three overall conversion strategies, TDH cutting rate (how many percent of the trees that have reached TD are harvested) and thinning intensity (using selective thinning) were varied systematically to provide a range of different conversion scenarios (Table 3). Selective thinning specifies thinning around elite trees according to the A-value concept (Johann 1982). Only neighbor trees located

Table 3 Settings in SILVA common to the three overall conversion strategies. Table layout adapted from Hanewinkel and Pretzsch (2000). D_{100} , diameter of the 100 thickest trees ha^{-1} (cm)

Procedure	Timing	Control parameter	Unit and quantity
Selective thinning	Conducted for a species from the first time $D_{100} \geq 15.0$ cm	A-value	4–6 depending on scenario
Target diameter harvesting	Harvesting a certain percentage of trees that have reached the target diameter	Target diameter	Silver fir, Norway spruce: 45 cm beech: 60 cm
	Initiated for all species from when spruce reach $D_{100} \geq 40.0$ cm the first time	Harvesting rate	30 or 50% depending on scenario

beyond a certain critical distance (dependent on the size of the neighbor tree) from the elite tree will not be removed in thinning. This critical distance is given by

$$\text{Dist}_{C,N} = \frac{H_C}{A} \cdot \frac{DBH_N}{DBH_C} \quad (1)$$

where $Dist$ is the distance between the elite center tree C and the neighbor tree N that is evaluated whether it should be thinned or not, H_C is the height of the elite tree, DBH_C and DBH_N is the diameter of the central and neighbor tree, respectively, and A is the A -value. Thus, lower A -value equals heavier thinning. The algorithm keeps selecting elite trees, one by one, and removing that selected tree's competitors according to the A -value, and continuing to select elite trees until no more competitors can be removed according to the selected A -value. For *Passive* and *Gaps*, the effect of only conducting selective thinning until reaching TD and hereafter only conducting TDH was tested (selective thinning was halted once $D_{100} > 40.0$ cm). This combination was not meaningful to test in *Shelterwood*, because preliminary results showed that an even-aged stand would emerge in the next generation unless the understorey was thinned.

Parameters tested included three overall conversion strategies, two different stand ages at conversion and three combinations of selective thinning and TDH cutting rate. Adding to these $3 \times 2 \times 3 = 18$ scenarios was four scenarios where selective thinning ceased at the initiation of TDH (only for

Gaps and *Passive* for both tested stand ages at conversion). Including *Reference* at both ages, 24 scenarios emerged.

We assumed all conversion scenarios required artificial regeneration (underplanting) to introduce fir and beech, either in gaps or under shelter/canopy. The regeneration module in SILVA was adjusted to provide 50% fir and beech in a gap when the small trees entered the growth model (> 7 m height). This species share in the underplanting was also used for *Shelterwood* and *Passive* in juvenile stands. However, since the underplanting in *Shelterwood* and *Passive* was not restricted to a smaller section of the stand like in *Gaps*, our opinion was that it was less realistic to simulate a complete underplanting of fir and beech below mature spruce stands, since the natural regeneration of spruce could be put to use under such conditions. Thus, here the goal was to have 50% of spruce and 50% fir/beech when the small trees entered the growth model (> 7 m height).

In *Shelterwood* and *Gaps*, underplanting was only simulated in the 5-year period when the shelter and gaps were created, while in *Passive*, underplanting to supplement natural spruce regeneration was continued until $H_{100} \geq 19$ m for one of the underplanted species (either fir or beech). This was to ensure establishment of the underplanting below the denser overstorey in *Passive*.

Evaluation of growth model

The ability of SILVA to make accurate prediction for uneven-aged spruce fir and beech stands was evaluated with

Table 4 Experiments used for validating simulation results. Soil nutrient scale: 1–6 (1 indicates very poor and 6 very rich soil). Soil water scale: 1–6 (1 indicates very low and 6 very high water supply)

Name	Experiment type	Treatments	Elevation (m)	Climate ^a (°C, (mm))	Soil nutrient availability	Soil water availability
MUE145	Conversion to uneven-aged forest	Single tree selection management	590	7.2, (1130)	3	3
KRE120-126	Regeneration experiment	Different harvesting techniques	850–1280	4–5 (1600–2000)	4	6
RUH110	Regeneration experiment	Varying basal area	880	6 (1600)	4	6
FRY129	Selection forest	Varying growing stock	720	6.5 (1200)	3	5

^aAverage annual temperature (and precipitation) during 1960–1990

data from experiments in Bavaria collected during the period 1953–2015 (Table 4). The collection included experiments with a long history of selection forest structure (FRY129, see Pretzsch 1985, 2019) and experiments where stands had more recently been converted to a higher structural heterogeneity (MUE145, KRE120-126, RUH110).

Firstly, the ability of SILVA to reflect the effect of growing stock on stand volume production was evaluated by visual comparison of species-specific actual and predicted growth in experiments where stand density reduction was included in the experimental design (experiments FRY129, RUH110 and KRE120-126). Specifically, using data from experiments with rather similar growing conditions to those specified in the simulations of the present study, we plotted species-specific volume production against stand volume for both experimental and simulation data. By this procedure, we aimed to reflect effects of differences in stand density between experiments and simulations in the visual assessment. Mixing proportions were calculated based on the stand density index (SDI, Reineke 1933) and adjusted according to the species-specific growing area requirements by using equivalence coefficients (Pretzsch and Biber 2016). Based on these mixing proportions, individual species growing stock and volume production were scaled to the one ha level. In this analysis, species constituting less than 20% of stand density were excluded from the analysis to avoid scaling error. Similarly, species making up more than 80% of stand density were excluded to compare only stands that had a certain level of mixing.

Secondly, we evaluated the ability of SILVA to replicate individual tree growth in uneven-aged forest using data from the experiment MUE145 (see Utschig 1997 and Schmitt 1994 for detailed description) because of its similarity to our synthetic stands regarding growing conditions, stand history and forest management. In the analysis, spatially explicit, individual tree data from MUE145 were fed into SILVA and predicted growth was compared to actual growth using the *lm* function in R. For the statistical analysis, we modelled residual dbh and height growth (observed growth on MUE145 plot 1 between 2006 and 2015 minus predicted growth from SILVA) with tree size (dbh and height, respectively) as the predictor variable. We hypothesized that zero slope of the regression line would reflect the ability of SILVA to replicate relative growth across tree sizes, while zero intercept would reflect our ability to replicate overall growing conditions. Since we merely adjusted the site conditions in SILVA according to site information on MUE145 from Table 4, we only assumed zero slope of the regression as our null hypothesis, recognizing that the settings in SILVA were unlikely to match actual site conditions perfectly. While the experimental plot MUE145, along with most of the other mentioned Bavarian experimental plots, was used as database for the parameterization of SILVA in

the late 1990s (Kahn and Pretzsch 1997), the growth and yield characteristics in the 20 years afterwards were so far not exploited for model parameterization.

Reference was not validated as the conversion scenarios because the simulator was well calibrated with experimental plot data from even-aged monoculture stands of spruce and can predict the growth of these in Bavaria with a sufficient accuracy (Pretzsch et al. 2002, 2006) (for a general validation of SILVA, see Pretzsch 2002 and Pretzsch et al. 2002). Such a validation was also performed in Hilmers et al. (2020).

Analyses

The different conversion scenarios were compared in terms of growing stock, mean annual increment (MAI) (of wood > 7 cm top diameter limit), mean structural heterogeneity during the 150-year conversion period, and expectation value (EV) (including later periods for the calculation of the eternal rotations part of EV). The growing stock is included in the analysis because it is an important determinant of the other variables used to evaluate conversion, but is itself not used as an evaluation criterion.

Economic yield

SILVA has inbuilt functions for calculating costs and revenues from timber harvesting. Grading for all species were set to mid-diameter grading, calculated with the log grading program BDAT (see Kublin and Scharnagl 1988) integrated into SILVA. Average timber prices for the different assortments were provided by the Bavarian State Institute of Forestry (LWF) for 2010–2014 (see Table 7 in Appendix).

Harvesting costs were calculated using Extended Forest Worker's Tariff (German: EST, for more information see KWF 2017). The costs are first of all based on time tables that describe the time spend per harvested cubic meter, dependent on species and log dimension (for more information see KWF n.d.). The other important components are the hourly salary (set to 30 €) and the general efficiency of the harvesting (set to 150%), these values are commonly used based on time studies (KWF n.d.). Skidding costs were set to 7.00 € m⁻³. Regenerations costs for planting were derived from Härtl (2015), which represent typical values for Bavaria. Planting density was set to 4000 trees ha⁻¹ (1.6 m x 1.6 m), amounting to the following values for fir and beech in the different scenarios; 2000 ha⁻¹ in *Shelterwood* when stand age at conversion was 30 years, 1333 ha⁻¹ in *Shelterwood* when stand age at conversion was 60 years (not 2000 ha⁻¹ because as mentioned, natural regeneration of spruce is also present), and a total for all three gaps of 867 ha⁻¹ in *Gaps*. In an attempt to reflect the likely higher costs in small-scale planting (such as underplanting in a

gap), the efficiency of underplanting in *Gaps* was set to only 50% of the efficiency in Härtl (2015). Due to the uncertainty in assessing the regeneration costs of *Passive*, a sensitivity analysis was used here to construct a range. In the high-cost scenario, planting costs were equal to the most expensive scenario—*Shelterwood* conversion at age 30 (2000 fir and 2000 beech ha⁻¹), while in the low-cost scenario the costs were based on a *Shelterwood* conversion using only 750 fir and 750 beech per ha⁻¹.

Having calculated the net return for each period, considering planting costs and net return for timber harvesting, EV for each scenario was calculated as the sum of discounted net returns. We reported the economic results using discount rates of 1 and 3%. In contrast to the other evaluation criteria,

$$EV = \sum_{t_c=s}^{C+s} (1+i)^{-(t_c-s)} \times NR(t_c-s) + \left[\left(\left(\sum_{t^*=0}^R (1+i)^{-t^*} \times NR(t^*) \right) \times \frac{1}{1-(1+i)^{-R}} \right) \right] \times (1+i)^{-C} \tag{3}$$

EV was calculated for the eternal future time periods. EV of *Reference* (Eq. 2) was calculated as the discounted net returns for the remainder of the first rotation (depending on whether the stand age at conversion was 30 or 60 years) and (in square brackets) subsequent eternal rotations of the cyclic regime (Faustmann’s “land expectation value”) initiated when the overstorey trees from the first rotation have been harvested and discounted with the length of the first rotation:

$$EV = \sum_{t=s}^{R_1} (1+i)^{-(t-s)} \cdot NR(t-s) + \left[\left(\left(\sum_{t^*=0}^{R_r^*} (1+i)^{-t^*} \times NR(t^*) \right) \times \frac{1}{1-(1+i)^{-R_r^*}} \right) \times (1+i)^{-(R_1-s)} \right] \tag{2}$$

where *i* is the discount rate, *s* is the stand age at conversion (30 or 60 years), *t* is the age of the stand during the first rotation, *NR(t-s)* is the net return in the first rotation obtained at time *t-s* (years from the initiation of the simulation) and *R_{r1}* is the rotation age of spruce (125 years) in the first rotation. Rotation age, net return and time of subsequent rotations are denoted with an asterisk. The rotation age is slightly longer in the subsequent rotations (*R_r^{*}* = 130years) because of the

reduction in site index in the present day climate norm (site index 31) compared to the climate under the former historic steady state conditions (site index 36). *R_r^{*}* cover the time period between harvesting the last overstorey trees in each rotation. We used the harvesting of the last overstorey trees in our definition of rotation (instead of initiation of regeneration) since the majority of the income was generated during the later regeneration cuttings.

For the conversion scenarios, EV was calculated as the discounted net returns for the 150-year conversion period plus the discounted net returns from eternal rotations of the converted system (square brackets) assumed to have some cyclic nature (Eq. 3). The eternal rotations part of the equation is finally discounted with the length of the conversion period:

where *t* is the time since the conversion was initiated plus *s*, *NR(t_c-s)* is the net return obtained at time *t-s*, i.e., years since the initiation of the conversion, during the 150-year conversion period *C*. An asterisk denotes the net returns and time of the converted system with a total conversion period of *C* and a rotation length of *R* to calculate the cyclic incomes.

Preliminary investigations showed that not all of the conversion scenarios reached a steady state within the 150-year conversion period. Also, the cyclic incomes, assumed to

occur when the stand had reached steady state, were not constant for harvestings on a ten-year basis—even when stands had a structure that resembled selection forest. Thus, it was decided that it was more realistic to use the net returns from the period 150–240 years to calculate the cyclic incomes (*NR(t^{*})*’s) for the different scenarios (240 years in the future was the technical limit for SILVA). In practice, *NR(t^{*})*’s were calculated using only one of the three created stands

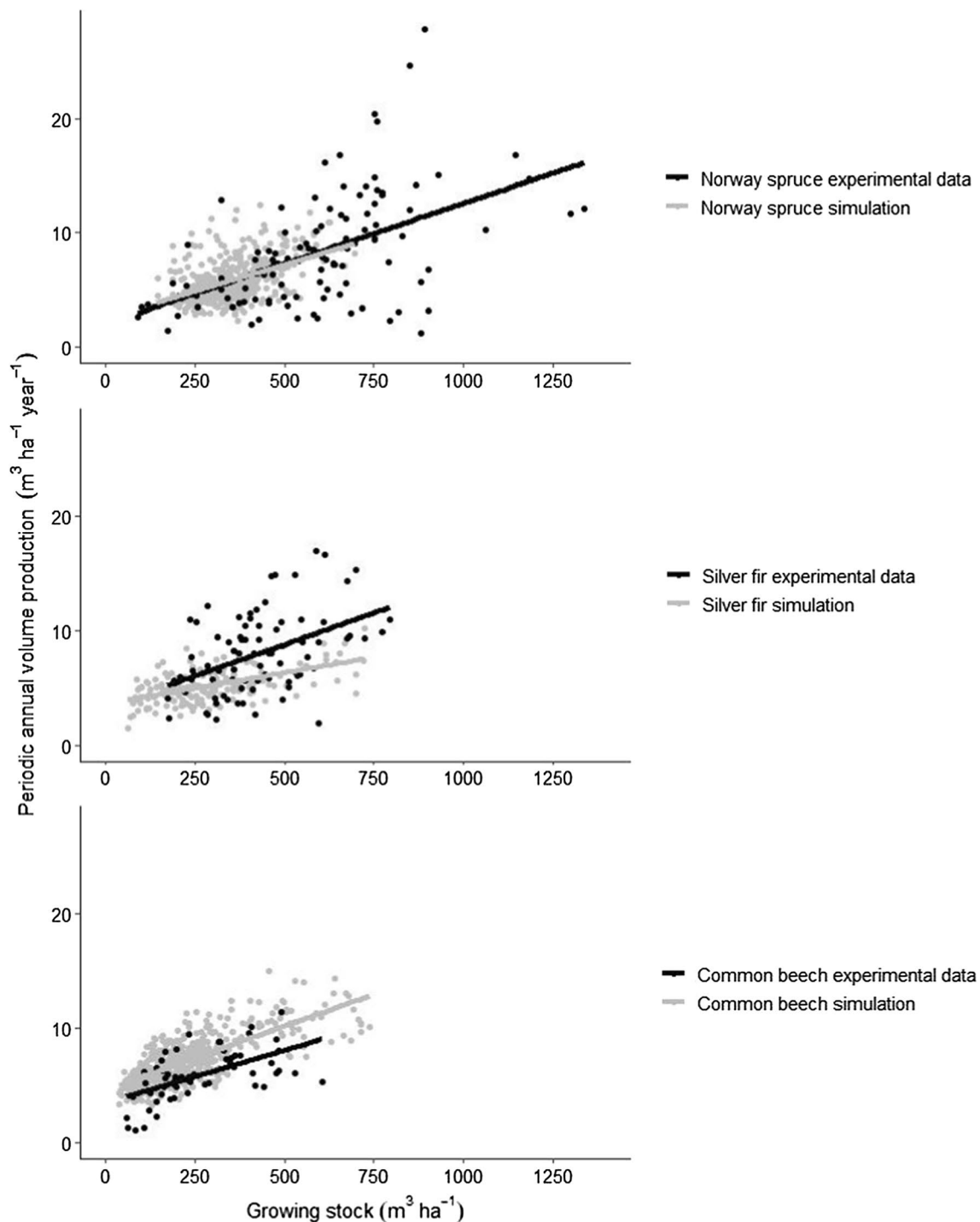


Fig. 2 Species-specific relation between growing stock and periodic annual volume production for conversion simulations and experimental plot data (illustrated with simulation stand 1). Results are scaled according to species-specific growing area requirements and scaled (as it was rather similar for the three different stands). It is important to emphasize that the period 150–240 years was solely used to calculate a more realistic cyclic income for the eternal rotations. The assessment was generally performed on the 150-year conversion period, and the period

up to one hectare. Common y-axis label for each species-specific graph and each point from the conversion simulations represents a simulated period. See Pretzsch (1985, 2019), Pretzsch et al. (2015, 2020) and Hilmers et al. (2019, 2020) for the experimental plot data 150–240 years was therefore not used in the evaluation of MAI and SPI.

It is also important to remember that the two different stand ages at the time of conversion represent different stands at different age. It should not be understood as

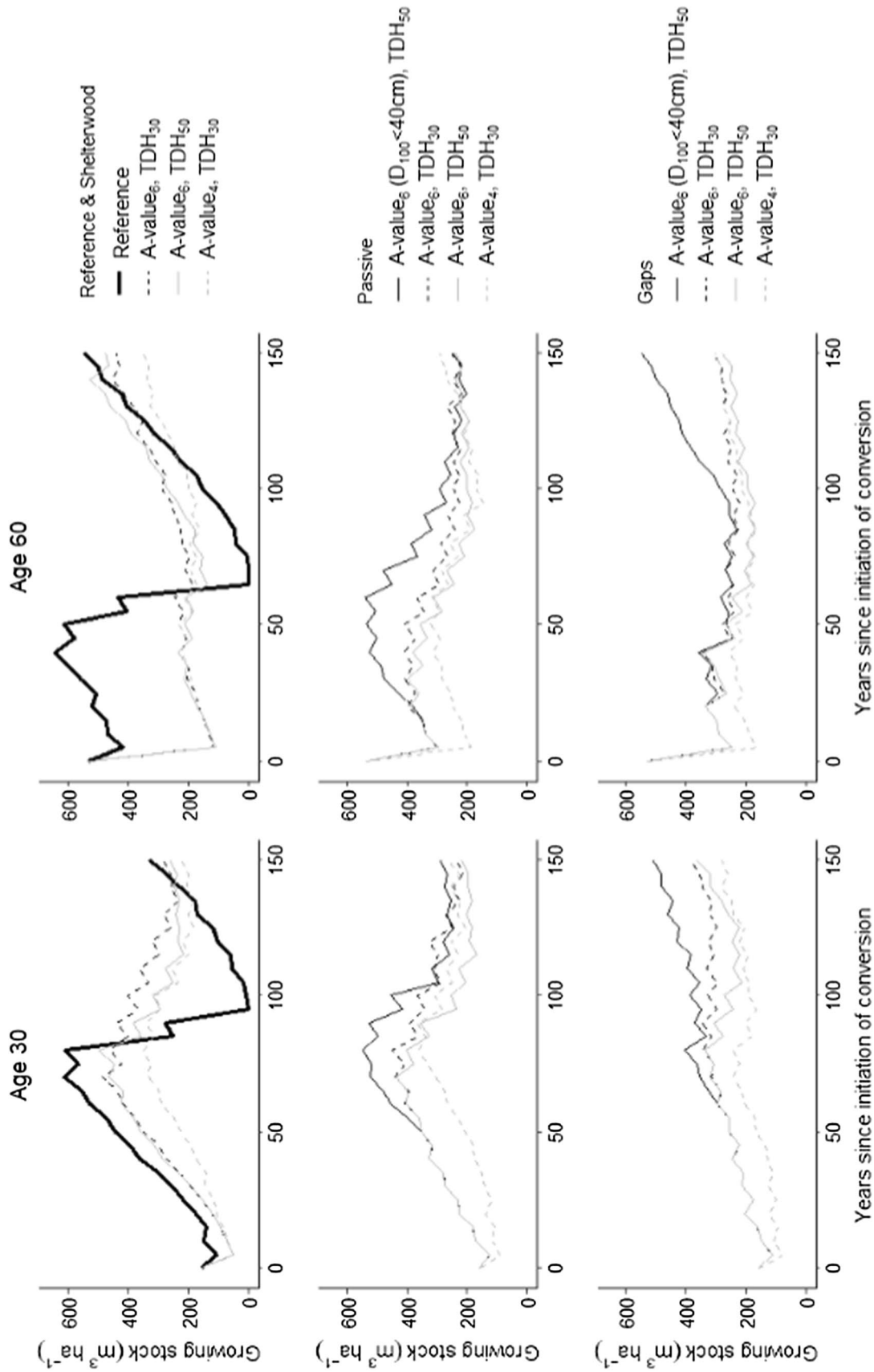


Fig. 3 Development of growing stock for simulated scenarios (illustrated with simulation stand 1), split up into overall strategies and stand age at conversion. TDH = target diameter harvesting rate (number in subscript refers to the cutting rate, e.g., 30%). A-value = the A-value component in the selective thinning approach by Johann (1982)

Table 5 Simulation results for scenarios during the 150-year conversion period (where the period 150–240 years are included only for the calculation of the cyclic income component of EV). Parentheses denote min and max of the conducted simulations. Expectation value is calculated for two different discount rates (1 and 3%). *TDH*, tar-

get diameter harvesting (number in subscript refers to the cutting rate, e.g., 30%). *A*-value = the *A*-value component in the selective thinning approach from Johann (1982). *MAI*, mean annual increment. *EV*, expectation value. *SPI*, species profile index. *i* = discount rate. “= as above. Underlined = assuming low regeneration costs

		MAI (m3-ha-1)	EV (1000€-ha ⁻¹)		SPI
	Age 30		<i>i</i> = 0.01	<i>i</i> = 0.03	
	Reference	9.0 (8.9–9.0)	36.7 (36.3–37.3)	7.9 (7.7–8.0)	0.35 (0.34–0.37)
<i>Passive</i>	A-value = 4, TDH ₃₀ “with low regeneration cost	5.9 (5.9–6.0)	20.7 (20.0–21.3)- <u>23.3</u> (22.6–23.8)	2.7 (2.5–3.1)- <u>5.1</u> (4.9–5.4)	1.35 (1.32–1.38)
	A-value = 6, TDH ₃₀ “with low regeneration cost	7.4 (7.2–7.6)	26.4 (24.9–27.7)- <u>29.0</u> (27.4–30.3)	3.9 (3.3–4.3)- <u>6.2</u> (5.6–6.6)	0.73 (0.67–0.77)
	A-value = 6, TDH ₅₀ “with low regeneration cost	7.2 (7.1–7.5)	27.5 (26.3–29.1)- <u>30.1</u> (28.9–31.7)	4.2 (3.6–4.7)- <u>6.6</u> (5.9–7.0)	0.82 (0.79–0.87)
	A-value = 6 (D ₁₀₀ < 40 cm), TDH ₅₀ “with low regeneration cost	7.7 (7.3–8.2)	27.3 (26.2–28.7)- <u>29.9</u> (28.8–31.3)	3.7 (3.2–3.9)-6.0 5.6–2.4)	0.59 (0.56–0.61)
<i>Shelterwood</i>	A-value = 4, TDH ₃₀	5.8 (5.4–6.1)	17.4 (16.2–18.4)	2.2 (1.5–2.9)	1.30 (1.27–1.32)
	A-value = 6, TDH ₃₀	7.2 (7.1–7.3)	22.4 (21.3–23.1)	1.8 (1.3–2.1)	1.17 (1.13–1.21)
	A-value = 6, TDH ₅₀	7.1 (7.0–7.2)	24.1 (23.7–24.4)	2.2 (1.9–2.4)	1.16 (1.13–1.18)
<i>Gaps</i>	A-value = 4, TDH ₃₀	6.0 (5.9–6.2)	21.5 (20.7–22.2)	5.5 (5.1–5.8)	1.52(1.50–1.54)
	A-value = 6, TDH ₃₀	7.7 (7.7–7.7)	28.2 (27.5–29.5)	6.3 (5.9–6.5)	1.49 (1.45–1.52)
	A-value = 6, TDH ₅₀	7.6 (7.4–7.8)	29.7 (28.9–30.7)	6.4 (6.0–6.6)	1.49 (1.44–1.53)
	A-value = 6 (D ₁₀₀ < 40 cm), TDH ₅₀	8.5 (8.3–8.8)	28.2 (27.7–29.3)	6.0 (5.7–6.1)	1.54 (1.50–1.56)
	Age 60				
	Reference	9.6 (9.4–10.0)	59.7 (58.6–60.6)	22.1 (21.5–22.7)	0.20 (0.17–0.24)
<i>Passive</i>	A-value = 4, TDH ₃₀ “with low regeneration cost	5.8 (5.7–5.9)	42.8 (42.2–43.8)- <u>45.4</u> (44.8–46.3)	20.7 (20.3–21.3)- <u>23.0</u> (22.6–23.7)	1.46 (1.39–1.55)
	A-value = 6, TDH ₃₀ “with low regeneration cost	6.1 (5.9–6.5)	43.3 (41.7–44.3)- <u>45.9</u> (44.3–46.9)	19.3 (18.3–20.0)- <u>21.6</u> (20.6–22.3)	1.04 (1.01–1.08)
	A-value = 6, TDH ₅₀ “with low regeneration cost	6.3 (6.1–6.6)	47.0 (46.2–47.9)- <u>49.6</u> (48.7–50.5)	20.4 (19.9–21.2)- <u>22.7</u> (22.2–23.5)	1.12 (1.09–1.17)
	A-value = 6 (D ₁₀₀ < 40 cm), TDH ₅₀ “with low regeneration cost	6.4 (6.1–7.3)	44.4 (44.1–44.8)-46.9 (46.6–47.3)	18.2 (17.8–18.5)-20.5 (20.1–20.9)	0.90 (0.75–1.03)
<i>Shelterwood</i>	A-value = 4, TDH ₃₀	5.5 (5.5–5.5)	41.4 (41.2–41.7)	22.9 (22.8–23.0)	1.41 (1.37–1.44)
	A-value = 6, TDH ₃₀	6.5 (6.2–6.9)	44.3 (43.3–45.8)	23.0 (22.7–23.5)	1.37 (1.34–1.40)
	A-value = 6, TDH ₅₀	6.7 (6.2–7.3)	46.8 (45.5–47.4)	23.4 (22.9–24.0)	1.32 (1.32–1.33)
<i>Gaps</i>	A-value = 4, TDH ₃₀	5.5 (5.1–5.7)	44.6 (43.3–45.7)	23.6 (23.4–23.8)	1.50 (1.49–1.52)
	A-value = 6, TDH ₃₀	6.5 (6.2–6.8)	46.6 (46.6–47.1)	22.8 (22.5–23.1)	1.54 (1.53–1.56)
	A-value = 6, TDH ₅₀	6.4 (6.2–6.5)	47.1 (47.0–47.2)	23.3 (22.9–23.6)	1.56 (1.53–1.61)
	A-value = 6 (D ₁₀₀ < 40 cm), TDH ₅₀	7.9 (7.6–8.1)	48.1 (47.6–49.0)	22.8 (22.5–23.1)	1.60 (1.57–1.61)

a single stand that is either converted at age 30 years, or converted after having waited another 30 years for the stand to become 60 years. Thus, the EV’s from the two different stand ages at conversion are not comparable.

Structural heterogeneity

The structural heterogeneity of the simulated forest was evaluated from the species profile index (SPI) (Pretzsch

1998); a modified version of the Shannon-index, which can also take vertical differentiation within the stand into account:

$$SPI = - \sum_{i=1}^S \sum_{j=1}^Z p_{ij} \cdot \ln(p_{ij}), \tag{4}$$

where *S* is the number of species in the stand, *Z* is the number of canopy layers in the stand, and *p_{ij}* is the species

proportion (in terms of stem number) of species *i* in the canopy layer *j*. The number of canopy layers in the stands is assumed to be three, extending from 0–50%, 50–80% and 80–100% of the maximum height of the stand (Pretzsch 1998). While a highly structured stand, such as a selection forest, will have high SPI approaching 2, very uniform stands will have low SPI approaching 0. Scenarios are compared in terms of the average SPI for all time periods during the 150-year conversion period.

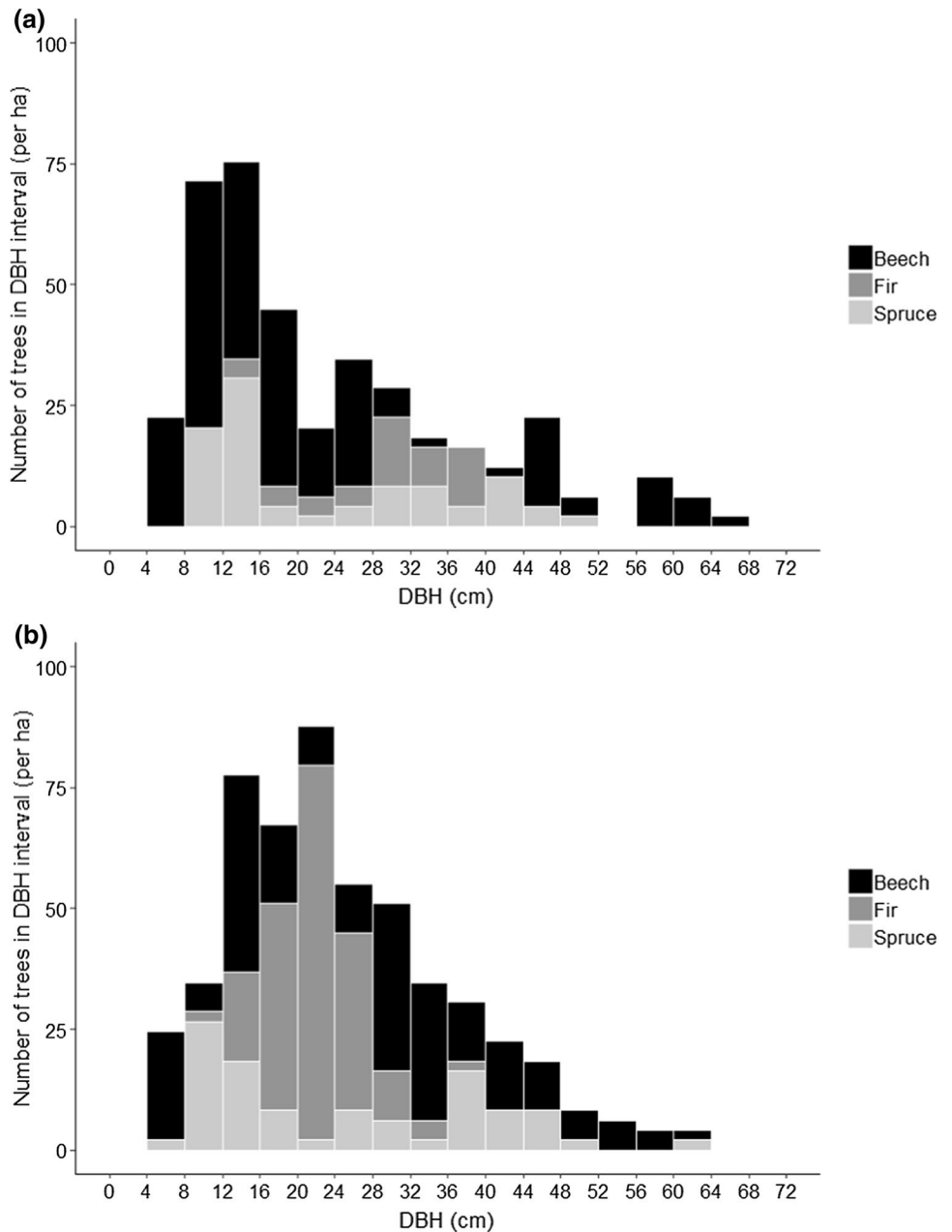
Apart from SPI, the scenarios were also evaluated by comparing the diameter distributions at the end of the conversion period, but this was merely a visual comparison.

Results

Evaluation of growth model

Figure 2 revealed that the volume production of beech was generally less on the experimental plots compared to the simulation while the reverse was true for fir. The slope of the trend between growing stock and volume production for fir was also steeper for the experimental plot data. The simulated volume production was closer to the experimental plot data for Norway spruce than for the other species.

Fig. 4 Diameter distribution after 150 years when stand age was 30 years at conversion, using the overall conversion strategy of gaps and target diameter harvesting was 50% a) with selective thinning b) without selective thinning



For MUE145 plot 1, SILVA was able to correctly specify relative DBH growth between 2006 and 2015 for trees no matter their size ($P=0.8$). However, the simulator was not able to predict the corresponding relative height growth ($P < 0.01$) across tree sizes. Trees below 25 m were generally predicted to grow relatively less than larger trees in the simulation compared to the observation on MUE145.

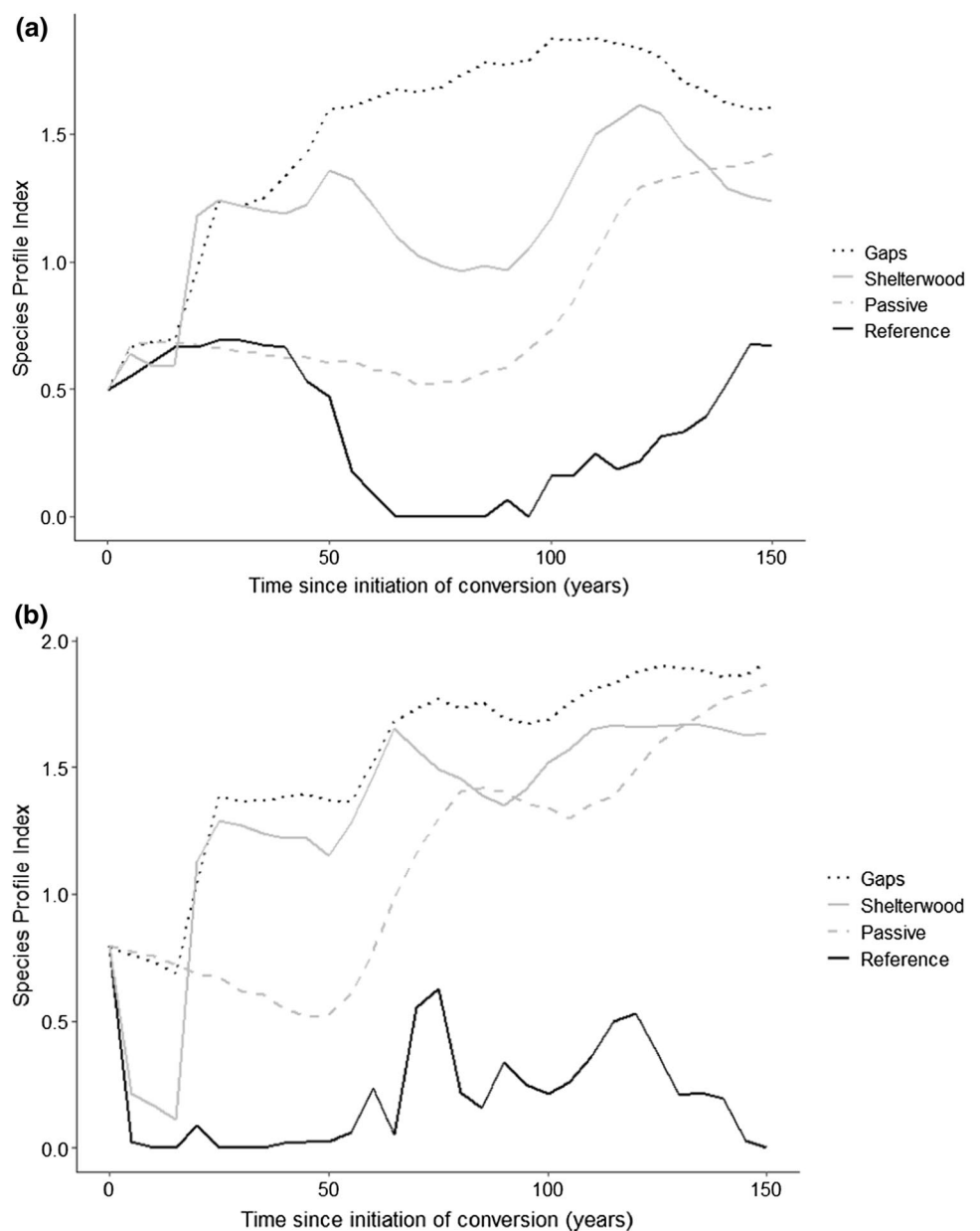
Effect on growing stock and volume production

The growing stock development illustrates the temporal differences in wood extraction among the different scenarios (Fig. 3). Reference results in a build-up of wood to more than 600 m³/ha at around age 105, when regeneration and harvesting by TD is initiated. This is followed by a sharp

decline when the remaining overstorey trees are harvested during the following 20 years. The growing stock in the conversion scenarios generally increases until the stand approaches TD; hereafter, it drops for about 50 years, after which it slowly starts to rise, illustrating the shifting number of trees that reach TD in the different periods. Gaps with only TDH after $D_{100} \geq 40$ cm deviates from the other gap scenarios by having a larger growing stock towards the end of the conversion period. The species-specific graphs in the supplementary materials show the slow build of beech and fir, which is especially slow for fir.

MAI of Reference was 9.0–9.6 m³ha⁻¹ during the conversion period dependent on stand age at conversion (Table 5). All conversion scenarios reduced MAI relative to Reference (6–43%). Reductions were largest when initiating the

Fig. 5 Average species profile index in the different conversion scenarios, when target diameter harvesting rate was 50% and selective thinning degree was according to A -value = 6 (see Johann (1982)). For stand age at conversion **a** 30 years, **b** 60 years



conversion at age 60 (18–43%) rather than at age 30 (6–36%). Scenarios with heavy thinning produced a lower MAI than the same overall conversion strategy with moderate thinning (5–22%). Adjusting TDH cutting rate only influenced MAI to a smaller degree ($\leq 3\%$). Excluding thinning operations after the trees reached their TD increased MAI (2–23%). *Gaps* resulted in roughly the same MAI as *Shelterwood* and *Passive*.

Effect on expectation value

Using a discount rate of 1%, Reference resulted in higher EV relative to all conversion scenarios no matter if conversion was initiated at age 30 or 60 (Table 5). Similarly, when stand age at conversion was 30 years and at a discount rate of 3%, Reference resulted in higher mean EV than all conversion scenarios. Oppositely, when stand age at conversion was 60 years and at a discount rate of 3%, *Shelterwood* and *Gaps* (and some *Passive* scenarios when low regeneration costs were assumed) resulted in higher EV than Reference.

Compared to the other conversion strategies, EV was generally higher for *Gaps*, unless low regeneration costs were assumed in *Passive*. *Shelterwood* generally resulted in lowest EV, except when stand age at conversion was 60 years, evaluated with 3% discount rate, where *Passive* resulted in the lowest EV (even when assuming low regeneration costs) and *Shelterwood* were similar to *Gaps*.

At a discount rate of 1%, early, heavy thinning decreased EV for all conversion strategies and both stand ages at conversion, while at a discount rate of 3%, the results were more mixed: 1) When stand age at conversion was 60 years, heavy thinning resulted in similar or higher EV, 2) when stand age at conversion was 30, heavy thinning decreased EV for all treatments compared to lighter thinning scenarios, except for *Shelterwood*. Scenarios without thinning after the trees had reached TD typically had a slightly lower EV, apart from in *Gaps* when stand age at conversion was 60 (and discount rate 1%). Differences between unthinned and thinned scenarios were however usually rather small, except in *Passive* when stand age at conversion was 60 years.

Increased TDH cutting rate always resulted in an increase in EV. The effect was typically largest when using 1% discount rate. EV of *Gaps* was generally not much affected by increasing TDH cutting rates compared to *Shelterwood*. For *Passive*, EV was not substantially affected when stand age at conversion was 30 years, but more so when stand age at conversion was 60 years.

Effects on structural heterogeneity

Reference resulted in a low SPI compared to all the conversion scenarios. Among the conversion scenarios, *Gaps* generally resulted in a higher SPI compared to *Shelterwood*

and *Passive*. This difference was especially apparent when stand age at conversion was 30 years.

Heavily thinned scenarios generally had higher SPI than moderately thinned scenarios, except for *Gaps* when stand age at conversion was 60 years. TDH cutting rates did not generally influence SPI, although a slight positive effect was observed in *Passive*. Excluding thinning after stands had reached TD decreased SPI in *Passive* and seemed to slightly increase SPI in *Gaps*. However, this increase in structural heterogeneity in *Gaps* was not confirmed when looking at the diameter distributions (Fig. 4a and b). SPI was generally higher when stand age at conversion was 60 years.

The structural development followed very different patterns in the three overall conversion strategies (Fig. 5) and were influenced by stand age at conversion. When stand age at conversion was 30 years, *Gaps* and *Shelterwood* resulted in a rapid initial increase in SPI, just 20 years after conversion was initiated. The structure in *Gaps* became increasingly more heterogeneous during the first 90 years after the start of the conversion, while large increases in heterogeneity started after 90 years in *Shelterwood* and in *Passive*. After 120 years of conversion, SPI was roughly similar in the different overall conversion strategies. When stand age at conversion was 60 years, the time before high SPI was reached in *Shelterwood*, and especially in *Passive*, was shorted considerably. Generally, we observed a strong increase in the beech proportion of the growing stock towards the end of the conversion period. While the stand percentage composed of beech and fir were practically similar during the early stages (as well as very low compared to spruce), stands were on average composed of 48% beech and 14% fir after 150 years at the end of the conversion period. The proportion of beech continued to increase during the 90-year interval after the end of the conversion period (between 150 and 240 years after conversion was initiated), accompanied by a decline in the proportion of conifers, driven by a decrease in the proportion of spruce.

Discussion

Conversion effects on volume production

Due to the heavy initial stand density reduction, all conversion scenarios reduced MAI relative to Reference. This was also generally observed in other simulation studies using dedicated gap cutting in SILVA (Hanewinkel and Pretzsch 2000) or heavy stand density reduction to initiate conversion in the simulator Heureka (Drössler et al. 2014). Both studies simulated conversion from even to uneven-aged spruce. Seemingly, our results were quite similar to these studies because the altered climatic variables in our study reduced spruce growth to be rather similar to fir and beech growth. Drössler et al. (2014) found similar growth for conversion

scenarios with the same growing stock whether thinning were differentiated spatially across the stand or applied homogeneously, but this could have been due to the use of the distance-independent Heureka simulator. This highlights the benefit of distant dependent individual tree models for conversion simulation, especially in our situation where quite contrasting conversion treatments were applied, and especially gap cutting and TDH created spatial heterogeneity.

Using SILVA, Hanewinkel and Pretzsch (2000) found that passive conversion by TDH did not have any practical influence on MAI, relative to traditional spruce management, while scenarios involving harvesting of gaps resulted in a considerable reduction in MAI. Contrasting this finding, *Passive* conversion using only TDH after $D_{100} \geq 40$ cm (the scenario that most closely mimicked the only TDH scenario in Hanewinkel and Pretzsch 2000) resulted in reduced MAI compared to Reference. Our analysis indicated that the longer simulation period in our study (150 years) compared to the 100-year period used in Hanewinkel and Pretzsch (2000) reduced growth since overstorey trees retained to old age had slower growth. Furthermore, in Hanewinkel and Pretzsch (2000), gaps had to be very large to accommodate spruce regeneration establishment. This resulted in large growth reduction compared to gap creation with fir and beech in our study, which required smaller gaps to ensure successful establishment in accordance with differences in light demand between spruce and fir/beech. This is in line with Hilmers et al. (2020) who, based on modelling in SILVA, demonstrated 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. It is also in line with Brunner et al. (2006), who simulated a transformation of spruce stands in SILVA by under-planting with beech in a gradually opened stand of spruce. Thus, of interest for practice, our results indicate that minor gaps do not necessarily result in a substantial growth reduction. Actually, *Gaps* generally produced a larger MAI than *Passive* in the simulations.

Although gap scenarios also achieved relatively high MAI in Hilmers et al. (2020) and Knoke and Plusczyk (2001), the relative production of *Passive* and *Gaps* is surprising, since the early cutting of gaps to benefit regeneration is normally expected to reduce production of overstorey trees. Contrasting the simulations in SILVA, results from mixed mountain forest experiment such as KRE120-126 and RUH110 suggested that cutting of gaps strongly decrease productivity, although such experiments have only been performed in old stands (> 100 years old).

How substantial MAI losses will be from cutting *Gaps* in younger stands is unknown. The effect of gap creation on stand productivity has, in comparison with the effect of species diversity, only been little investigated (Bourdier et al. 2016). Our results might partly be due to the favorable

conditions for regeneration in small gaps (Brunner and Huss 1994). The reduction in MAI relative to Reference was more pronounced for strategies that involved heavy and late stand density reductions than for scenarios with early and more moderate interventions. We did not find any substantial effects on MAI when varying the TDH harvesting rates in the conversion scenarios. In comparison, Brunner et al. (2006) compared TDH using different TDH limits following shelterwood and found substantial differences in overstorey growth but these results are incomparable to our study because Brunner et al. (2006) did not include understorey growth.

Few studies have compared growth across different conversion scenarios, and none have involved different ages for the onset of conversion. However, the observed mechanisms are biologically meaningful (e.g., Bryndum 1980 finds that thinning reduces growth more at older age).

The transferability of our results for conversion compared to Reference to other site conditions is especially affected by the site-specific relative productivity between spruce, beech and fir. Under warmer and drier conditions, Norway spruce will be less competitive relative to beech and fir. The relative performance of the different conversion scenarios is less affected by site conditions, or at least in terms of how site conditions are specified in SILVA. Nevertheless, a warmer and drier climate will result in more reduced growth at the later development stages (Pretzsch 2009), pointing to lower optimal TD as well as a higher rate of TDH. In our case, spruce growth was already substantially reduced from our climate adjustment compared with Huang et al. (2017) and Pretzsch et al. (2014).

Effects of conversion on the expectation value

Conversion generally resulted in reductions of EV, most likely mainly as a result of premature harvest of trees at the onset of the conversion and reduced growth of the remaining stand. The exception was when stand age at conversion was 60 and using a discount rate of 3%.

Several studies have found that increasing the discount rate increases the profitability of conversion scenarios relative to traditional management as a consequence of increased harvesting during the early conversion phase (Hanewinkel 2001; Knoke and Plusczyk 2001; Price and Price 2006). In line with these results, our study showed that active scenarios were relatively more profitable than *Passive* and Reference, when stand age at conversion was 60 years and using a discount rate of 3%. When stand age at conversion was 30 years, the revenue from early heavy harvesting to initiate conversion was apparently not enough to compensate for the expensive underplanting and loss of growth and later harvesting opportunities.

A general concern when initiating conversion at later stages is that the proportion of trees that are harvested later than their financially optimal time of cutting may be relatively

large (Knoke 2009) rendering the conversion at old age less profitable. However, in our study the stumpage price curve obtained from the Bavarian State forest (see Table 7 in Appendix) did not dictate a significant increase in the price per unit for increasing diameter beyond 25 cm. Also, MAI during the individual rotations in Reference reached maximum when D_g reached app. 34 cm. Consequently, the optimal DBH at harvesting would likely be less than the TD of 45 cm used for spruce, especially for large discount rates (Meilby and Nord-Larsen 2012). When initiating conversion at age 60 years (see Table 1), a large part of the trees felled would therefore be at or close to the optimal harvesting diameter increasing the relative profitability of active conversion at high discount rates. It can be argued that a smaller TD should have been used in all scenarios (both for Reference and conversion) given the underlying stumpage prices. This would have resulted in earlier initiation of TDH, which would have benefited Reference more than the conversion scenarios because of the higher growing stock in Reference when TD is reached. This illustrates the importance of stumpage prices when comparing conversion and traditional management (Knoke et al. 2001). It also illustrates an issue in economic evaluation of traditional management vs. conversion that has previously been raised (Price 2003): is it meaningful to consider conversion at high discount rates as superior when it is merely caused by overly long rotation periods resulting from silvicultural tradition? This point seems to be valid for Bavarian conditions. This also highlights that a secondary TD for spruce, e.g., 35 cm, which would have resulted in a significant reduction in rotation length, should be considered in studies analyzing the advantage of conversion.

A number of practical assumptions made in our study may have affected the relative performance of the Reference and conversion scenarios. In general, we assumed that wood quality resulting from the different scenarios would be similar. Although this may not be true, the combined effect of time required for this to manifest itself in the economic calculations and the discounting, likely render this of minor economic importance (Schou et al. 2012). We also made assumptions about the regeneration costs and as could be seen from the sensitivity analysis in *Passive*, regeneration costs could have a considerable effect on the results. However, our assumptions likely did not heavily influence the relative results between scenarios. *Gaps* was penalized in terms of planting costs due to the assumption of no use of natural regeneration in the initial plantings when stand age at conversion was 60 and twice as expensive planting costs per plant due to the small scale planting. Still, this scenario came out with an overall better EV result than *Shelterwood*. The relative ranking between *Passive* and *Gaps* was to some degree affected, but the regeneration costs in *Passive* were in any case highly uncertain.

More importantly, we also considered harvesting costs fixed across different thinning types and stand structures

similarly to other studies (e.g., Hanewinkel 2001 and Knoke and Plusczyk 2001). Studies have shown that this is probably not a realistic assumption and have found that harvesting costs differ in the scale of roughly 2.5–5 €/m³ across different harvesting regimes and generally find that clearcut is the most efficient harvesting technique (Pausch 2005; Price and Price 2008, 2006). To illustrate the effect of differences in harvesting costs, consider a conversion scenario with high EV (*Gaps*, A -value₆, TDH₅₀). For this scenario, penalizing harvest costs in uneven-aged forests would likely reduce EV 1,600–3,300 € using 1% discount rate and 400–1000 € using 3% discount rate (almost similar for both stand ages at conversion). Such an assumption could be realistic across most conversion scenarios since harvesting costs between different uneven-aged forest systems (group selection and single tree selection) have been found to be rather similar (Suadani and Fjeld 2001). This would not have a large impact on the results, although if assuming the highest penalty for harvesting in uneven-aged forest, Reference would be more at level with the most profitable conversion scenarios for stand ages at conversion of 60 years and using a discount rate of 3%.

The effect of different natural hazards (especially wind throw) on the economic output in practice often exert large influence on the choice of conversion method. Nonetheless, longevity of overstorey trees and risk of windthrow was not included in this study despite being a severe constraint to conversion efforts on many sites in Europe. Comparison to MUE145 and regional survival probability curves in Neuner et al. (2015) shows that the predicted longevity of overstorey trees during a conversion scenario could be realistic for the simulated site. This is especially because spruce in mixed stands have higher survival probability, compared to pure stands, at older age (see also Griess et al. 2012), which could have implications during the later stages of conversion. However, the longevity of overstorey spruce would be much less on more shallow rooted clayey sites in many regions of Europe (Henriksen 1988), especially in windy climates. Wind throw is often the cause of stand destruction following shelterwood thinning in spruce (Löf et al. 2010; Reventlow 2020). Experiments have also found that heavier shelterwood thinning down to 10 m² ha⁻¹ further increases the risk of wind throw (Reventlow 2020). In relation to our study, including the risk of windthrow may reduce the expectation value of the conversion scenarios substantially. However, large parts of central Europe experience significantly lower wind speeds compared to more oceanic areas (Troen and Petersen 1989). This explains why conversion efforts can take place at older age in such regions, e.g., in the Munich area as described in Matthes and Ammer (2000). While shelterwood thinning in stands taller than 18 m is considered very risky in oceanic Europe (Larsen and Skov- og Naturstyrelsen 2005), such operations are recommended in stands higher than 25 m for

areas situated in 500–1400 m altitude in Bavaria (Bayerische Staatsforsten AöR 2018). At present, a wind risk model for use in complex forest (based on the work of Hale et al. 2012, 2015) is undergoing testing. At the time when this study was conducted, the model was still under development, but this model has a large potential to make simulation studies more realistic, especially for more wind exposed areas.

Recent studies have criticized the use of only net present value (and supposedly EV), for the estimation of the economic value of different land use alternatives (Knoke et al. 2020). The argument is especially that flexibility (e.g., of liquidity) is not given any weight, although studies have shown flexibility to be of high importance for landowners in decision making (Yemshanov et al. 2015). Uneven-aged stands is often considered to have higher cash flow flexibility than even-aged stands (Nord-Larsen et al. 2003), unless forest owners manage to create a normal forest, which is rarely achieved (Knoke 2012). However, conversion to uneven-aged stands also represents a long-term investment decision, especially when expensive underplanting is carried out, which can be considered a flexibility constrain on the forest owner.

Structural heterogeneity

Our results demonstrated large differences in the time required to convert even-aged spruce to uneven-aged spruce, fir and beech depending on the applied strategy, especially when initiating conversion at age 30. Similar results were derived for conversion of spruce plantations to uneven-aged spruce, fir and beech when stand age at conversion was 30 years in Hilmers et al. (2020) and to uneven-aged spruce in Hanewinkel and Pretzsch (2000), although the latter study did not include a shelterwood scenario. The faster structural development in *Shelterwood* when initiating conversion at age 60 may, at least partly, be attributed to our defined scenarios. For conversion at age 60, we allowed natural regeneration of spruce to be incorporated in the underplanting below the *Shelterwood*. Thus, according to the definition of SPI, this raises the structural development.

The uniform shelterwood is a common outset for conversion in spruce (Brunner et al. 2005; Schütz 2001) and has been recommended for a range of stand conditions (e.g., Larsen and Skov- og Naturstyrelsen 2005 and Nyland 2003). Our results question the use of uniform shelterwood thinning as a method to achieve large structural heterogeneity rapidly, at least in young stands. Here, *Shelterwood* had a tendency to create quite homogeneous regeneration, subsequently resulting in a homogeneous two-storied stand for a long time (roughly 100 years). This observation is in line with observations made in practical forestry and the lack of differentiation in many shelterwood systems is often the reason why conversion to uneven-aged stands fails in practice (Matthes and Ammer 2000; Schütz 2001). However, shelterwood conversion may

be advantageous in situations where conditions for regeneration are harsh, especially due to late spring frost, high browsing pressure or heavy competition from weeds. Under such difficult conditions, observations show that gaps of 30 m diameter can cause high mortality among underplanting of susceptible species (Reventlow 2020). Furthermore, *Shelterwood* allows for a fast change in species composition compared to *Passive* and *Gaps*, which can be beneficial when converting spruce stands that are unstable due to, e.g., bark beetle attacks.

The slow development of SPI in *Passive* was caused by the time required for the regeneration to establish. It took shorter time before TDH was initiated when stand age at conversion was 60 years, increasing mean heterogeneity. Despite our results, it seems possible to achieve acceptable underplanting establishment without having to reduce the shelter density to the degree visualized in *Shelterwood* (Pretzsch 2019; Schmitt 1994; Utschig 1997) and hence to achieve larger heterogeneity earlier in *Passive*. Conversion using a passive approach actually has the potential to provide faster structural heterogeneity than uniform shelterwood, since thinning is more spatially differentiated and results in a wider diameter distribution in the overstorey. This is also illustrated from the high SPI in *Passive* when used in combination with heavy thinning. But this potential is however dependent on a spatially heterogeneous thinning and continuous regeneration, which both somewhat lacked in our study. It should also be mentioned that denser overstorey (which is typically the case for passive conversion) reduces height growth of the underplanting, slowing conversion (Reventlow 2020). This is also clear from MUE145 where conversion is clearly progressing faster in the plot where the most intensive shelter density reduction was undertaken (Pretzsch 2019).

In general, thinning was needed to ensure long-term heterogeneity—even in *Gaps*. Using only TDH, the growing stock builds up as beech and fir grows without being thinned until they finally reach the TD after a long time (after 180 years). The same growing stock build-up pattern as in *Gaps* was not observed in *Passive* because the establishment of fir and beech was much less complete and the regeneration had not had a long time to develop at the end of the conversion period (but SPI was still low due to the long time before regeneration was established). While *Gaps* using only TDH had a high SPI, comparison with the diameter distributions showed very limited ingrowth.

This also illustrates a flaw of SPI, since all tree heights below 50% of max tree height in the stand were treated similarly. Still, the problem with other structural indices such as the Gini index (Gini 1912) and the diameter differentiation index (Gadow and Fuldner 1995) was that they give weight to extremes more than they give to variation. As an example, a stand with recent shelterwood thinning would have a higher diameter differentiation index and Gini index compared to a selection forest (since the indices responds mostly

to observations that are far apart, such as a small tree in the understorey and a large tree in the overstorey), although the selection forest is clearly more heterogeneous.

The marked increase in beech share of the growing stock towards the end of the conversion period (and beyond) was due to the complete dominance of beech in the predicted natural regeneration (after the underplanting had reached maturity and started bearing seeds). The beech dominance in the simulated natural regeneration seemed excessive at first. However, comparison with experimental plot data from KRE120 and FRY129 showed that such dominance can be expected. This is despite that these experiments are located at higher elevation having higher water supply and lower temperature than the simulated sites, meaning that spruce has a competitive advantage (Pretzsch 2009). Practical guidelines for the Bavarian alps up to 1200 m altitude also suggest that frequent pre-commercial thinning is needed to sustain both species of conifers because of the strong competitiveness of beech regeneration (Bayerische Staatsforsten AöR 2018). Thus, for most sites and many types of silvicultural systems, it will be a struggle against nature to introduce and keep fir in a mixed forest system with beech.

Evaluation of SILVA simulations and procedure

Some deviations were expected for the comparison of species-specific volume production across different growing stocks since both treatments and growing conditions differed somewhat between experimental and simulated stands. The slightly colder conditions (Table 4) lead to lower growth of beech on the experimental plots at a certain growing stock. Conversely, silver fir growth seems to be under-predicted by SILVA, as previously reported (Mette et al. 2009), likely due to the smaller database used for the parameterization of this species. In contrast, spruce volume growth was well predicted, probably because of the large database used for parameterization (Pretzsch et al. 2002). These results imply that the simulated growth dynamics could be realistic for beech and spruce but with some deviations for silver fir.

We made no attempt to conduct a formal validation of the regeneration and mortality modules in Silva due to the erratic nature of seedling establishment and mortality (Vanclay 2012) as well as the sparse data available on regeneration and mortality in such development stages. However, we observed that when shelter basal area exceeded roughly $12 \text{ m}^2\text{ha}^{-1}$, predicted survival of the underplanting was almost none. This is in contrast to high survival rates observed for beech and fir planted below spruce shelter having basal areas exceeding $20 \text{ m}^2\text{ha}^{-1}$ (Ammer and Weber 1999; Pretzsch et al. 2015; Reventlow 2020). We suspect that this relation between stand density and regeneration survival could be one reason why productivity is relatively high in *Gaps*

relative to *Passive* due to the lack of regeneration in *Passive*, resulting in less growth.

The predicted regeneration mortality in SILVA at higher basal areas had implications for the design of the conversion scenarios, which had to accommodate the successful establishment of regeneration. Hence, the stand density reduction applied in some of the conversion scenarios (especially *Shelterwood*) exceeded what would be necessary in practice (see, e.g., Utschig 1997 and Pretzsch 2019).

Whether a 150-year conversion period can be considered sufficient to incorporate the effect of different conversion treatments is an important discussion. Firstly, the investigated treatments were initiated early following conversion. Treatments were initiated no later than 65 years after initiation of conversion (TDH, when stand age at conversion was 30 years). Furthermore, SPI generally reached steady state within the 150-year conversion period. What was not reached was, as already mentioned, equilibrium in terms of species distribution. From that perspective, a longer conversion period would have been preferable. Our approach is relatively long compared to other studies (Hanewinkel 2001; Hanewinkel and Pretzsch 2000; Hilmers et al. 2020; Knoke and Plusczyk 2001), especially considering that we also used some data from 150–240 years for calculating EV.

Conclusion

Simulation is by definition a simplification of the real world in terms of variables that affects stand development. Hence, the challenge of this study was to produce consistent, scientific but also relevant and realistic simulations across a variety of treatments when converting plantations to heterogeneous forest. Despite limitations, the conducted simulations represent an overview on how different factors influence the expected trajectories of conversion. The results indicated that especially creation of several gaps combined with moderately heavy thinning, and a high rate of target diameter harvesting resulted in a favorable combination of high productivity and economic yield (across tested discount rates) and fast development of high structural heterogeneity. On the other hand, shelterwood conversion generally resulted in inferior structural development and economic results, especially when conducted at an early stage. Thus, shelterwood conversion should mainly be used in conversion situations where a fast change of tree species is a necessity. Using a more passive conversion was harder to evaluate, because the used simulators prediction of regeneration was sensitive to overstorey density. But the economic result was generally not better than in gaps, and structural development would be slower.

In order to simulate scenarios more realistically, especially on sites with larger wind exposure than Central

Europe, growth models and risk tools for natural hazards should be linked together more closely than was possible in our study. Furthermore, it is important that more research is devoted to increase the accuracy of regeneration models since regeneration is a crucial part of the conversion process.

Appendix

See Table 6 and 7.

Table 6 Overview of management in Reference and overall conversion strategies (stand age at conversion = 60 years and heavy thinning in conversion scenarios) during the 150-year conversion period. Number dictates order of action. “[U]” marks periods where there is underplanted. *TB*, thinning from below. *TDH*, target diameter harvesting. *TA*, thinning from above. *TF*, thinning for future trees. *TS*, Selective thinning

Period (age ¹)	H ₁₀₀ ¹	Reference	Passive	Shelterwood	Gaps
1 (60)	26				
2 (65)	27	TB	TS, [U]	1: Creation of shelter, 2: TS, [U]	1: 1 st Gap, 2: TS, [U]
3 (70)	28		[U]		
4 (75)	29	TB	TS [U]	TS	TS
5 (80)	30		[U]		
6 (85)	31	TB	1: TDH, 2: TS, [U]	1: TDH, 2: TS	1: 2 nd Gap, 2:TDH 3: TS, [U]
7 (90)	32		[U]		
8 (95)	33		1: TDH, 2: TS, [U]	1: TDH, 2: TS	1: TDH, 2: TS
9 (100)	33		[U]		
10 (105)	34	TDH	[U]	1: TDH, 2: TS	1: 3 rd Gap, 2: TDH, 3: TS, [U]
11 (110)	34		1: TDH, 2: TS, [U]		
12 (115)	34	TDH	[U]	1: TDH, 2: TS	1: TDH, 2: TS
13 (120)	35		[U]		
14		TDH	1: TDH, 2: TS, [U]	1: TDH, 2: TS	1: TDH, 2: TS
15			[U]		
16			1: TDH, 2: TS, [U]	1: TDH, 2: TS	1: TDH, 2: TS
17			[U]		
18		TF	1: TDH, 2: TS, [U]	1: TDH, 2: TS	1: TDH, 2: TS
19					
20		TA	1: TDH, 2: TS	1: TDH, 2: TS	1: TDH, 2: TS
21					
22		TA	1: TDH, 2: TS	1: TDH, 2: TS	1: TDH, 2: TS
23					
24		TB	1: TDH, 2: TS	1: TDH, 2: TS	1: TDH, 2: TS
25					
26		TB	1: TDH, 2: TS	1: TDH, 2: TS	1: TDH, 2: TS
27					
28		TB	1: TDH, 2: TS	1: TDH, 2: TS	1: TDH, 2: TS
29					
30		TB	1: TDH, 2: TS	1: TDH, 2: TS	1: TDH, 2: TS
31					

¹Only shown for the period until the initial spruce stand is harvested

Table 7 Bavarian timber prices from 2010–2014 used for the simulation, dependent on species and mid log diameter

	€ m ⁻³ dependent on mid log diameter (cm)										
	0–5	5–10	10–15	15–20	25–30	25–30	30–35	35–40	40–50	50–60	60–
Norway spruce	0	29	57	74	83	90	90	90	90	90	89
Silver fir	0	0	44	68	79	84	85	85	85	87	90
Beech	0	0	64	62	61	59	56	64	71	81	85

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Data availability Readers may contact the corresponding author for getting access to data.

Code availability Readers may contact the corresponding author for getting access to simulator and code.

Declarations

Conflict of interest The author declares that they have no competing of interest.

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