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Under storm risk, economic productivity of Norway spruce (*Picea abies* (L.) H. Karst) in monoculture shows sharper decline than in mixture with European beech (*Fagus sylvatica* L.)

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Abstract

Key message By calibrating and validating a forest growth model for seven species in Germany and coupling it with a wind damage simulator, we specifically estimated the impact of wind damage on the net present value of Norway spruce and European beech in mixture and monoculture. Under risk, the net present value of spruce managements saw the sharpest declines, although the highest end net present value was still obtained through a heavily thinned spruce monoculture.

Context Wind damage is one of the most important risks to Central European forests, and adaptation measures are essential.

Aim Adaptive management strategies should simultaneously account for forest production and wind risk. We simulated the effect of adaptive measures on wind-risk in German forests.

Methods A process-based forest growth model, "3-PG Mix", was recalibrated and coupled with the storm damage risk model "Lothar". We investigated the effect of thinning regimes on wind risk in monoculture and mixed species stands. The net present value of the simulated regimes was calculated and compared (risk vs. no risk).

Results Spruce regimes achieved the highest net present values when risk was not considered. Considering risk in spruce and beech mixtures and monoculture, all regimes reached values below 3000 € ha^{-1} by year 120. The exception was a heavily thinned spruce monoculture at 4507 € ha^{-1}, being the most profitable regime under risk.

Conclusion We conclude, on the basis of this modelling study, that heavy thinning reduced storm risk and maintained a higher net present value in spruce. Species mixture of beech and spruce saw net present values levels remain more constant under risk, while beech monoculture increased.

Keywords 3-PG, Forest growth modelling, Forest wind damage, Climate change, Mixed forest

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This article is part of the topical collection on "Risks of (not) adapting - Socio-ecological conflicts in forest management: risks of (not) adapting?"

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1 Introduction

1.1 Process-based modelling and model description

Empirical yield and growth models have been developed and used to predict forest growth and productivity while assuming stable climatic conditions. In contrast to empirical models, process-based forest growth models estimate the physiological processes in the development of forest stands, sensitive to changes in climatic conditions, rather than generating results based on measured growth from forest inventory data. The processes contributing to the growth of biomass are modelled through fitted functions, such as gross primary production, canopy conductance and transpiration. By modelling these processes, it is possible to make plausible estimations of future forest growth under changing climate (Landsberg and Sands 2011) and make adaptive decisions to safeguard main forest processes and functions (Yousefpour et al., 2012). The process functions are defined by parameters which are dependent upon local factors such as soil water content, soil fertility and climatic variations, which influence the projected growth of the biomass.

The process-based forest growth model "3-PG" (Landsberg and Waring 1997, see Appendix, Table 2 for list of all abbreviations) has been chosen as the model to represent the forest stand development in Germany because of its ability to predict biomass growth under changing climatic conditions (in terms of precipitation, temperature and atmospheric CO_2 and management). In addition, the 3-PG model is freely available, simple enough to require few inputs but also complex enough to react to variations in climatic, soil and species, inter alia. It is also relatively simple to parameterise for various forest types and has been validated for the functioning of its sub-models (Forrester et al. 2020).

3-PG was initially used in Oceania and the USA to quantify the effects of climate variation on forest biomass growth (Landsberg & Waring 1997; Coops et al. 1998; 2001) and was utilised for numerous species, including conifers (*Pinus*; *Pseudotsuga* spp.) and broadleaves (*Eucalyptus*; poplar) (also see Gupta & Sharma 2019 for complete overview). The model has been used extensively for modelling of *Eucalyptus* plantations without the need to conduct extensive ground measurements in temperate and later tropical conditions (Landsberg and Waring 1997; Almeida et al. 2009). 3-PG has also been used to estimate the effects of climate on site productivity over time (Waring et al. 2014) and the effect of tree age on carbon storage (Zhao et al. 2009). For coniferous species, it has been used to estimate possible variation in tree growth, due to climate variation, from such species as Douglas fir (*Pseudotsuga menziesii* (Mirbel)) (Coops et al. 2010) and *Pinus taeda* (Bryars et al. 2012) and has been applied to estimate carbon sequestration in Sitka spruce (*Picea sitchensis*) plantations in Scotland (Minunno et al. 2010). The model has also been calibrated for broadleaf species such as birch (*Betula* spp.) (Potithep and Yasuoka 2011) and European beech (*Fagus sylvatica* L.) in Baden-Württemberg (Augustynczik et al. 2017), as well as for European beech and Norway spruce (*Picea abies* (L.) H. Karst) by Trotsiuk et al. (2020) in Switzerland to reflect the local growth conditions. Nölte et al. (2020) made a calibration for sessile oak (*Quercus petraea* (Matt.) Liebl.) in Germany, and a more comprehensive calibration of the main European tree species was carried out by Forrester et al. (2021), utilising data from Switzerland.

3-PG mix is an expansion to the model 3-PG which accounts for deciduous and mixed species stands (Forrester and Tang 2016). 3-PG mix includes an expanded canopy and light absorption model and accounts for the dormant season of deciduous species and diameter distributions of the given species. The ability to mix tree species makes 3-PG mix appropriate to German forests, where a number of species and age classes need to be represented in a single stand to provide a realistic representation of the forest composition and development.

1.2 Mixed forest stands and forest disturbances

Establishment of mixed forest stands has been widely recognized among adaptive measures as safeguarding forest processes and functions under climate change (Pretzsch et al., 2017). Moreover, mixed stands have been shown to be important in the mitigation of economic consequences of climate change. For example, mixed stands of spruce and beech were shown to be more robust to disturbances than pure stands, as well as the effects of stand mixtures on stand resistance, which can have high economic importance (Friedrich et al. 2019). However, there are potential limitations and strengths to forest diversification, in the sense that diversification can reduce economic risk and improve multi-functionality, but multi-functionality can also come at the price of economic losses (Knoke et al. 2017). Therefore, an evaluation of various scenarios of forest growth under future climate change conditions is needed to assess the most promising management strategies in the future.

Forest disturbances also play a major role in defining forest conditions and their growth. Therefore, it is crucial to integrate forest disturbances in the modelling of forest processes. Wind is the most important disturbance agent in Germany, causing large-scale damages, e.g. the Wiebke, Lothar and Kyril storms which occurred in the years 1990, 1999 and 2007 respectively (Jung et al., 2016). Wind risk can be mitigated by manipulation of individual tree diameter and is our chosen method of assessing storm damage risk, as suggested by Mason and

Valinger (2013). Following on from previous studies (Zell and Hanewinkel 2015; Gardiner et al. 2016; Müller et al. 2019), we implement a wind disturbance module in 3-PG to account for wind in modelling and management of forest stands.

Having developed the coupled model, we will utilise it to test potential management strategies in German forests, with a focus on the effect of thinning on storm damage mitigation. We also assess the degree to which 3-PG's thinning functions allow for estimation of future biomass growth, with and without storm impacts. Considering this, we calculate economic outcomes of the resulting management scenarios with the coupled model. The study is essential to provide process-based decision support systems for finding economically efficient adaptive solutions for wind prone forests.

The main goals of this study are as follows: (1) to calibrate a process-based model 3-PG to simulate monocultures and mixed species stands in Germany, (2) integrate a disturbance module in 3-PG to account for wind disturbances, and (3) evaluate alternative forest composition (monoculture vs. mixture) and management strategies (no thinning, BAU thinning, intensive thinning and light thinning) to mitigate wind disturbance risk. We analyse the forest growth and wind risk of different strategies from an economic perspective, observing the best-performing strategies.

2 Methods

2.1 Modelling approach

For our simulations, the process-based forest growth model 3-PG mix (Forrester and Tang 2016) was utilised, applying Bayesian inference to calculate the parameter values governing the model's processes (as per, e.g. Augustynczik et al. 2017; Trotsiuk et al. 2020; Forrester et al. 2021). We calibrated a range of species within Germany, so that future analyses can be undertaken with various mixture compositions. The chosen study areas contain a number of climatic and site conditions within Germany, which require each tree species to be calibrated for the range of conditions contained within the country's national boundaries. The chosen tree species in this study are European beech, Norway spruce, Scots pine (*Pinus sylvestris* L.), Douglas fir (*Pseudotsuga menziesii*), European larch (*Larix decidua* Mill.), sessile oak and silver fir (*Abies alba* Mill.).

The calibration of the model's tree species mentioned above was carried out using a dataset based on three transects running through regional gradients (e.g. soil type, soil water saturation and climatic condition) in Germany (see Fig. 1). These location-dependent site values of diameter, height and BA were derived from empirically modelled growth functions (Schmidt et al., 2020). The growth periods were divided into three different age classes of 34 to 64, 64 to 94 and 94 to 119. These age classes correspond to the time over which the German National Forest Inventories took place (1987 to 2012) and the progressions of growth in the transect data mirror the growth over this period.

Given that the stem density plays a fundamental role in the biomass calculations in 3-PG mix, and the stem number per stand in the calibration data was not available, stem density was derived from the diameter and BA stand values. The progression in stand density with age was then interpreted as stand thinning, where the model reaction to the removal of stems due management in turn affects the development of stand biomass. The calibration and validation process is described in detail in Appendices 2 and 3.

2.2 Storm damage risk model "Lothar"

For the purpose of our analysis, 3-PG mix model was integrated with the storm damage risk model "Lothar" (Schmidt et al. 2010). Lothar is a statistical storm damage model and is based on an empirical dataset of large-scale forest inventories. These inventories were a combination of the German National Forest Inventory Data (1987 and 2002), as well as an inventory carried out in the aftermath of the Lothar storm on 26 December 1999. Through a comparison of standing trees before and after the Lothar storm, the critical wind speed during this storm event could be identified (Schmidt et al. 2010). This model operates at the individual tree or stand level and utilises the height and diameter of the trees, as well as four Topex-to-distance variables (Scott and Mitchell 2005) available at each stand location. These Topex variables are sums of the terrain slopes measured in the eight cardinal directions from the given location. Negative Topex values are the summits of hills or ridges, near-zero values correspond to plains and positive values represent valleys or depressions (Schmidt et al. 2010). The output diameter and height distribution vectors from 3-PG mix are then used as input variables for Lothar. The inputs for the Topex variables are derived from four separate raster layers from which the stand coordinates indicate the relative Topex value. In addition, the model also considers the coordinates of the stand location, in terms of the Gauss-Kruger coordinate system, as another factor which influences the probability of storm damage. The individual tree species are also divided into categories regarding their windfirmness. These categories are beech/oak, fir/Douglas fir, pine/larch and spruce. The formula (1) of the Lothar model is given by the following:

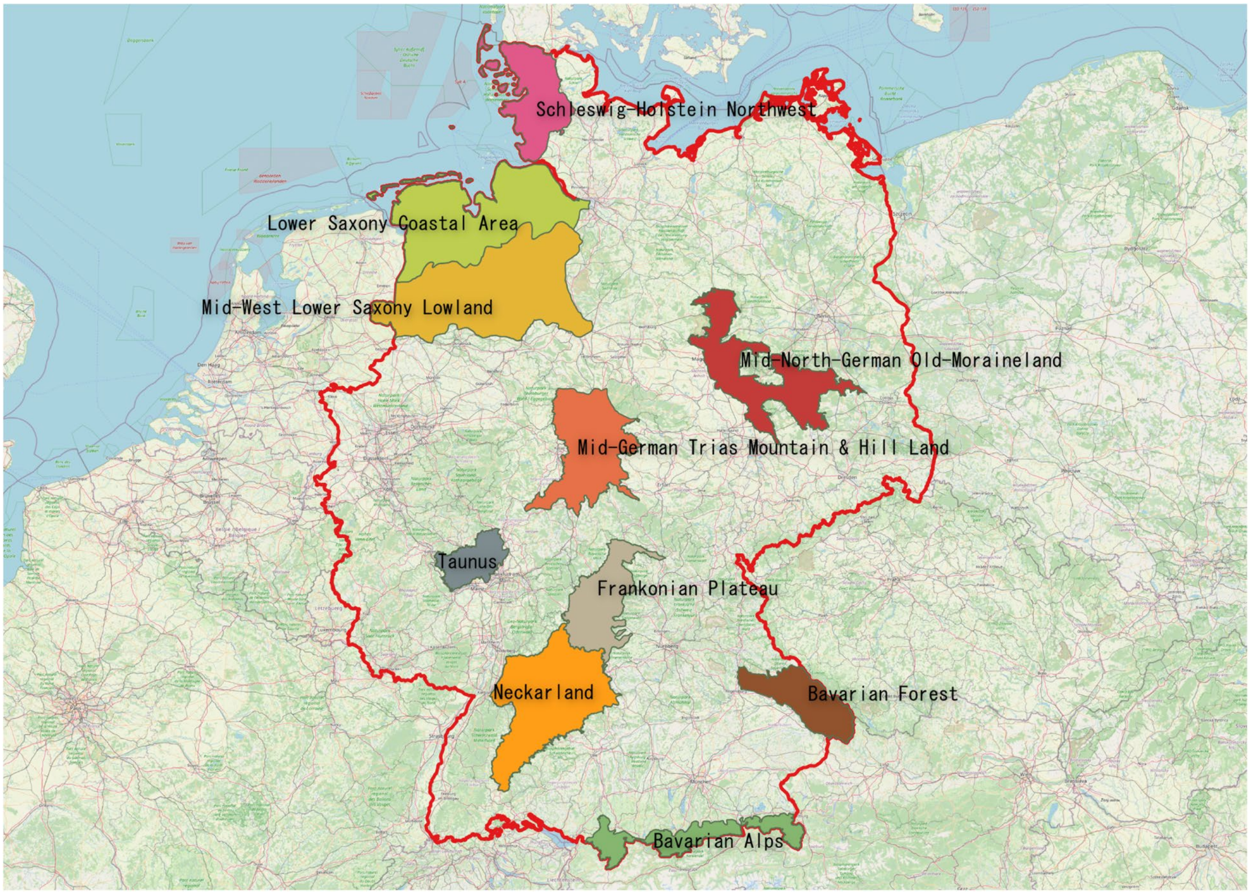

Fig. 1 The German growth regions used for the calibration

$$g(\pi_i) = \beta_{1i}Species + \beta_{2i}log(DBH) + \beta_{3i}log(h) + \beta_{4i}TopexToDistance1 + \beta_{5i}TopexToDistance2 + \beta_{6i}TopexToDistance3 + \beta_{7i}TopexToDistance4 + f(N,E) \quad (1)$$

where $g(\pi_i)$ is the damage probability of a given species, β is the species parameter and the four Topex-to-distance variables are the slope angle sums in the four wind directions, and the f(N,E) is a smoothing function based on the stand coordinates (Schmidt et al. 2010).

The damage probability generated is also integrated to 3-PG mix so that it removes the proportion or stems relative the given probability. However, this can also function so that only the probability is provided but without the stem removal, in which case the stand does not react to storm damage probability. As with the thinning function in the 3-PG model, when a storm event occurs, foliage, stem and root biomass are removed, which is based on the difference in stem number before and after the event and the biomass thinning values applied for that species.

2.3 Stand species composition effect

In addition, an analysis was undertaken to show the difference in growth between a specific species grown in monoculture and mixture. Each species was simulated starting with 500 stems ha^{-1} and ran from 30 to 120 years old, except when a species and management-dependent minimum stem density was reached. To test the behaviour of the tree species in mixture, we made simulations considering each species first in monoculture and then in mixture with each other species. The additional mixture species had the same stem number as the target species, i.e. 250 stems ha^{-1}, to a total of 500 stems ha^{-1}, as for monoculture.

We simulated monocultures and mixed stands to wind disturbance and evaluated the storm damage risk related to the mixture or monoculture growth attributes. We stocked monocultures with 500 stems ha^{-1}, and for mixed stands, each species was allocated 250 stems ha^{-1}. Additionally, we evaluated the effect on wind risk based on 4 management strategies, no thinning, BAU thinning, heavy thinning and light thinning. In the no thinning strategy, the only removal of stems occurs through mortality or storm damage. All thinning regimes are carried out in 10-year intervals. The BAU, heavy and light thinning values were based on those used by Augustynczik et al. (2020) (which were in turn derived from thinning levels used in the German National Forest Inventory, in the case of BAU). The remaining heavy and light thinning strategies were species-specific stem removal intensities, greater and lesser than the BAU strategy respectively. However, these thinning rates sometimes resulted in the stand being thinned to a level where all stems were removed from the stand. Therefore, we capped the number of allowable remaining stems for each species. For mixed species, we halved this number for each species. Once the capping took place, we then left the stand unmanaged for an additional 40 years, at which point we considered to be an end harvest, if the rotation end had not already been reached, in order to examine the volume and net present value development after thinning. Here, we evaluated the influence of these management strategies on the growth parameters affecting the wind damage risk, i.e. the height and diameter, as well as the influence of the particular tree species properties on said risk. We use the Mann–Whitney *U*-test and *T*-test to compare the difference in storm damage risk in these aforementioned cases.

2.4 Risk-moderated biomass growth

We compared these risk-modified biomass outputs with the biomass outputs not considering risk, in order to determine which management strategies enabled the best performance, with and without wind risk. No climate change scenario was considered in this study, in order to evaluate stand growth under "normal" climatic conditions. In order to relate the wind damage risk to potential biomass growth, we simulated the same management strategies and mixtures, but the biomass outputs were moderated by the risk probability, updated on an annual time scale. The *P*-value was considered to be a fraction of stems removed by a storm event. A comparable method was also utilised by Müller et al. 2019, where the Lothar model was also utilised to calculate percentages of removed timber from forest stands after a storm event. In this way, the removed biomass from a storm event functions in the same manner as the thinning function in 3-PG and, depending on the level of risk, biomass will be removed from the foliage, stem and root variables.

2.5 Net present value calculation

An economic analysis of the simulated monocultures and mixtures and management strategies was carried out for two common species (Norway spruce and European beech) in Germany forestry, which can broadly represent conifer and broadleaf forestry, in order to quantify the relative effectiveness of each scenario considering net-discounted revenue and damage risk. The net present value was therefore calculated (2) as follows:

$$NPV(i,N) = \sum_{t=0}^{N} \frac{R_t}{(1+i)^t} \qquad (2)$$

where t is the stand age, i is the discount rate and R_t is the net revenue, considering revenues and costs. We used timber prices and harvesting costs for Baden-Württemberg between 2000 and 2016, as also utilised in Zamora-Pereira et al. (2021) for their economic analysis. We also account for wood quality partitions of the analysed species, according to the yield tables for Baden-Württemberg (Landesforstverwaltung Baden-Württemberg, 1993). We applied a discount rate of 2%. Extracted volume and end rotation volume were separated into 10-diameter classes with a corresponding net revenue per m^3. The sum of the discounted revenues was then calculated to give a net present value for each month of the simulation. In the case of storm-damaged timber, we consider stems to be removed based on the damage risk probability. Any stems removed due to storm damage are consequently devalued to half of their value for a given diameter class, as per Müller et al. (2019). A guideline line as to the codes used to for calibration, Lothar model linkage with 3-PG and net present value calculation are provided in Appendix 5. The calculations were carried out.

3 Results

3.1 Tree species parameter calibration, validation and volume estimation

The final derived parameter set is shown in Appendix Table 4. In Fig. 2, in some cases, the prior parameters performed better; however, for the majority, there was improvement, when comparing the prior parameter set with the posterior in estimating the calibration data. The greatest improvement was the BA estimation of Scots pine, which saw increases in the range of > 40%. The BA of Douglas fir in contrast saw a greater part of the spread in the negative area of the *x*-axis, the widest outlier being < −25%. However, the overall spread of this variable

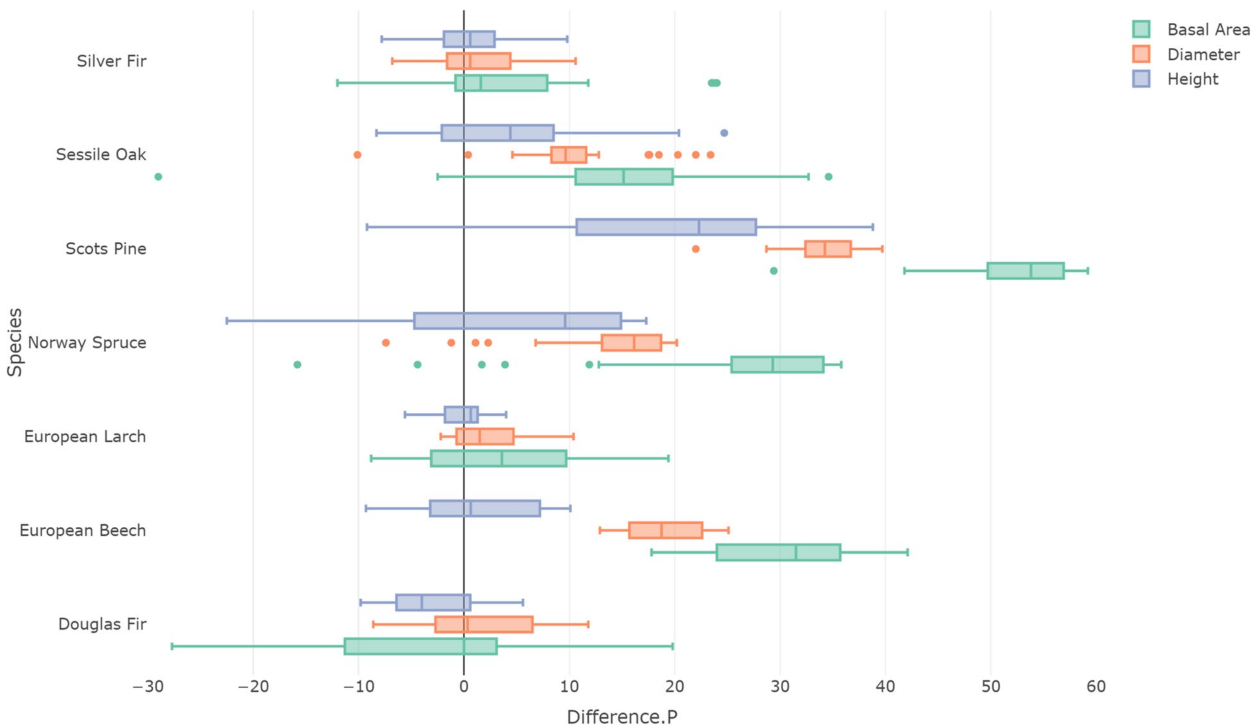

Fig. 2 The differences in PBias between the prior parameter set and the posterior. The tree species are shown along with BA, DBH and height values. In this case, the X-axis shows the difference between the initial parameter set (from Forrester et al. 2021) and the parameters derived from the calibration. The negative range of the *X*-axis indicates where the derived parameters made inferior estimations of the variables and the positive range where the estimations were superior. On the zero line, there was neither improvement nor worsening of the performance

Table 1 Mean percentage bias (Pbias) and standard deviation (SD) values for the plots used for validation of DBH, height, basal area, and volume, as well as the mean of all four biases

	DBH %	Height %	BA %	Volume %	Mean %
Spruce Pbias	+ 1.0	+ 13.0	+ 4.2	− 2.5	+ 3.9
Spruce SD	14.1	24.9	33.0	30.9	25.7
Beech Pbias	+ 3.3	+ 6.7	− 28.3	− 26.5	+ 11.2
Beech SD	39.6	18.1	23.9	33.1	28.7
Douglas fir Pbias	+ 3.5	+ 10.6	− 24.6	− 5.7	− 4.0
Douglas fir SD	10.9	26.1	39.9	14.3	22.8
Larch Pbias	+ 5.6	+ 8.8	+ 21.1	+ 31.7	+ 16.8
Larch SD	11.8	8.1	26.4	36.7	20.7
Silver fir Pbias	+ 9.2	+ 2.1	+ 84	+ 13.0	+ 8.2
Silver fir SD	18.1	9.1	23.7	9.2	15.0
Pine Pbias	− 3.3	− 7.4	+ 4.5	− 23.6	− 7.4
Pine SD	30.1	14.7	65.7	59.6	42.5
Oak Pbias	+ 7.4	− 18.5	+ 2.4	− 20.8	− 7.4
Oak SD	25.6	4.5	31.7	31.3	23.3

is ~ 45%, with a median value at the origin of the *x*-axis, so the height estimation of Douglas fir is the most uncertain of the height estimations. The height of Norway spruce and Scots pine, while also uncertain (ranges of > 35% & 45%, respectively), their distribution is negatively skewed. Apart from the BA and height of Douglas fir, all median values showed an overall reduction in the bias.

Error bias is an important tool to indicate the reliability in the prediction of a given output variable, where the percentage bias shows the accuracy of the estimation of an output variable and the standard deviation given the precision of the bias calculation. In Table 1, silver fir shows the highest DBH bias, while the lowest DBH bias was in Norway spruce. For height, the highest was sessile oak, and the lowest was Silver Fir. For BA, the largest bias was in beech, and the lowest was sessile oak, and European larch had the highest volume bias and spruce the lowest. Taking a mean of all four of the output variables, European larch had the highest mean bias and Douglas fir the lowest. To speak of the deviations in the bias for each species, the species with the highest mean deviation was Scots pine, and the lowest was silver fir. The largest deviations in the data came from BA and volume of pine, while the lowest were the heights of larch and oak.

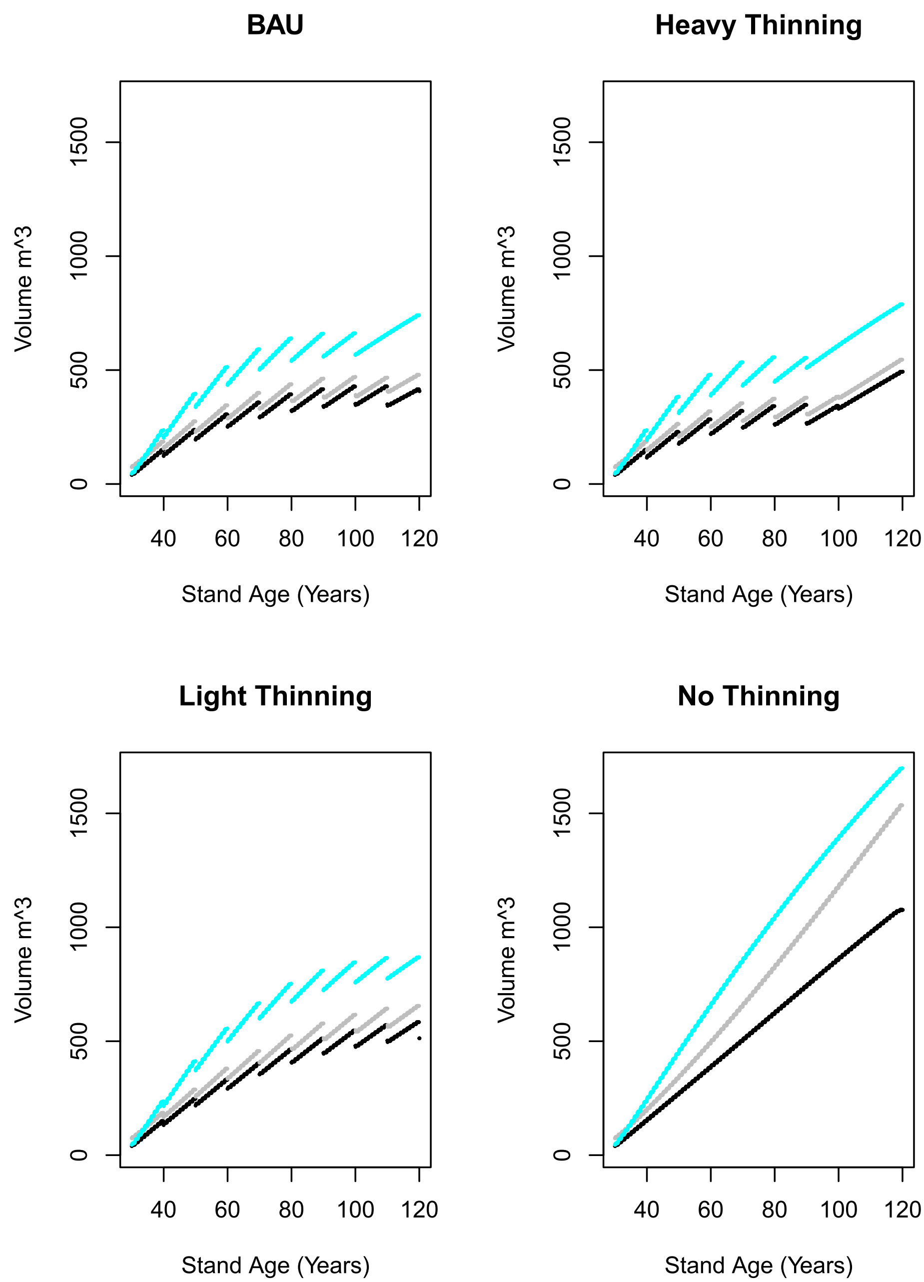

Fig. 3 The four thinning regimes, with their related volume growth, are shown for beech monoculture (black), spruce monoculture (blue) and beech/spruce mixture (grey). The *y*-axis shows the extracted volume, and the *x*-axis shows the stand age from 30 to 120 years old. In the thinning regimes, extraction occurs in 10-year intervals until a minimum stem number is reached

Additional results of the calibration and validation are shown in Appendix Figs. 17 and 18.

In Fig. 3, both for monoculture and mixture, the no-thin regime had the highest volume at the end of the rotation, 1011 m^3 ha^{-1} (beech), 869 m3 ha-1 (spruce) and 1535 m^3 ha^{-1} (mixture). For the other three regimes, total monoculture and mixed volume achieved similar levels. The extracted volume is shown in Fig. 4, and of the three regimes, light thinning spruce monoculture also resulted in the highest level of extracted volume at 539 m^3 ha^{-1} followed by BAU mixture at 490 m^3 ha^{-1}.

Additional growth projections of the remaining species in mixture with beech can be found in Appendix Figs. 19–26.

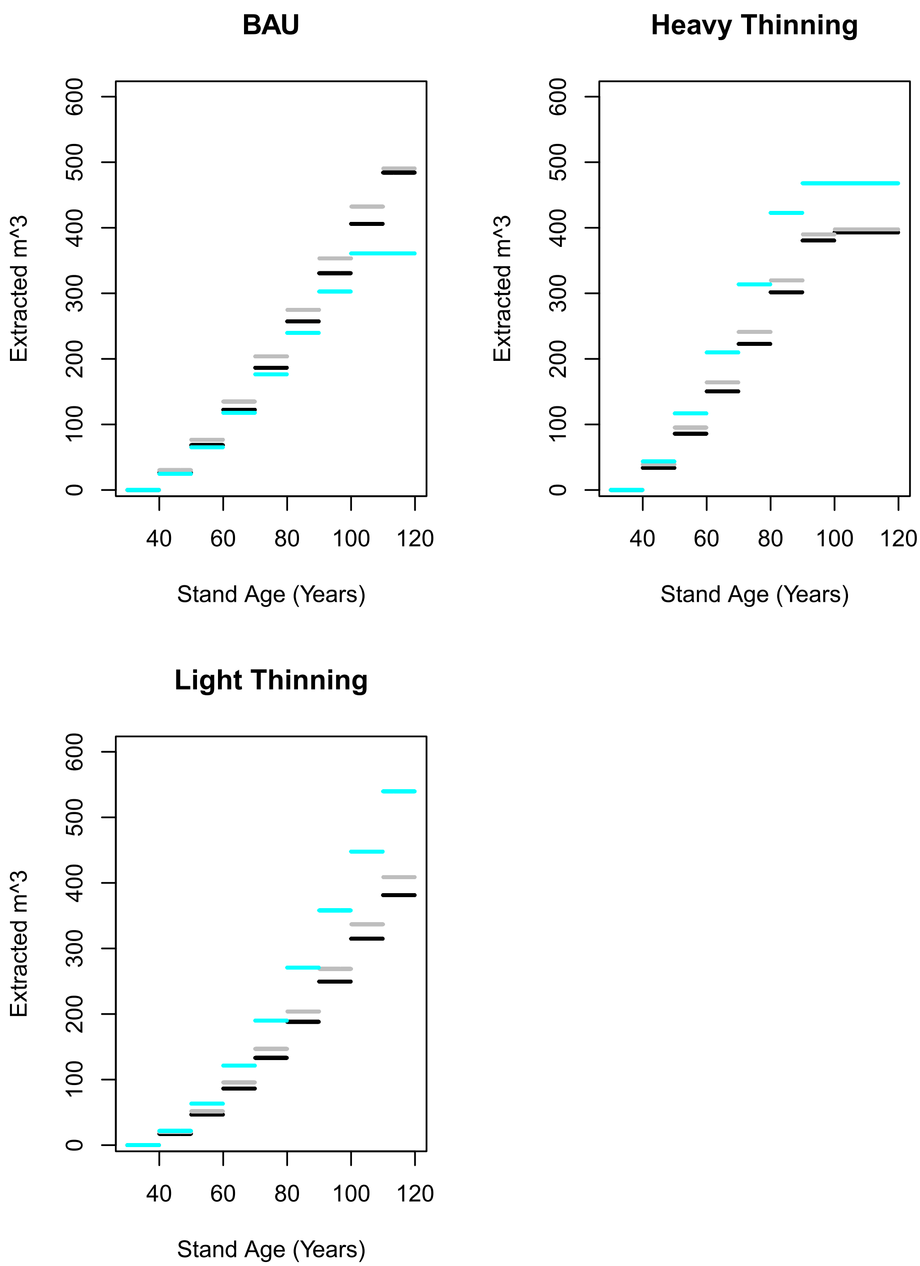

Fig. 4 The extracted volume of the three thinning regimes is shown for beech monoculture (black), spruce monoculture (blue) and beech/spruce mixture (grey). The *y*-axis shows the extracted volume, and the *x*-axis shows the stand age from 30 to 120 years old. Thinning occurs in 10-year intervals until a minimum stem number is reached

3.2 "Lothar" model coupling

Figure 5 makes evident how beech, oak and pine display the overall lowest storm damage risks, while Douglas fir and Spruce have overall the highest. As can be seen in the figure, the higher risk species do not exceed a 0.25 *P*-value. This is consistent with Schmidt et al. (2010), where the sensitivity analysis of the site coordinates of the "Lothar" model shows a strong north/south gradient in the *P*-value. The *P*-value range further to the north tends to be in upper range, ~ 0.2–0.75, and further south, the range is rather ~ 0–0.2. Our analysis falls into the latter category since the site coordinates for the plot used are easting 3,460,000 and northing 5,380,000.

Appendix Figs. 27 and 28 show the storm risk plotted against the height for the four thinning types in mix and monoculture simulations of beech and spruce, as well as the other species. The maximum height reached depends on the management type in this case, but the

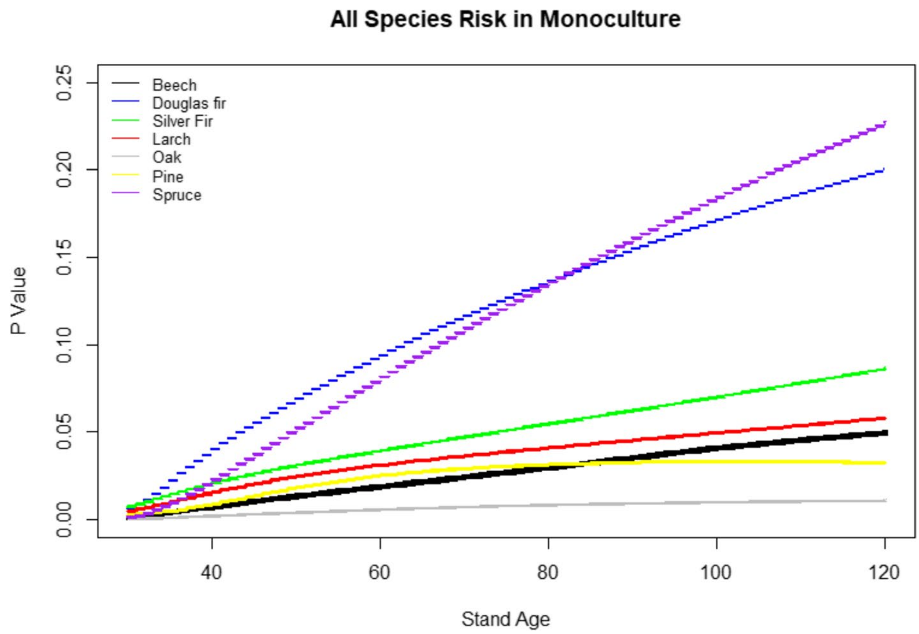

Fig. 5 The progression of storm risk (*p*-value, *y*-axis) with age (30–120 years, *x*-axis) in no thin monoculture stands of the given species. Species are delineated by colour: beech, black; Douglas fir, blue; Silver fir, green; larch, red; oak, grey; pine, yellow; spruce, purple

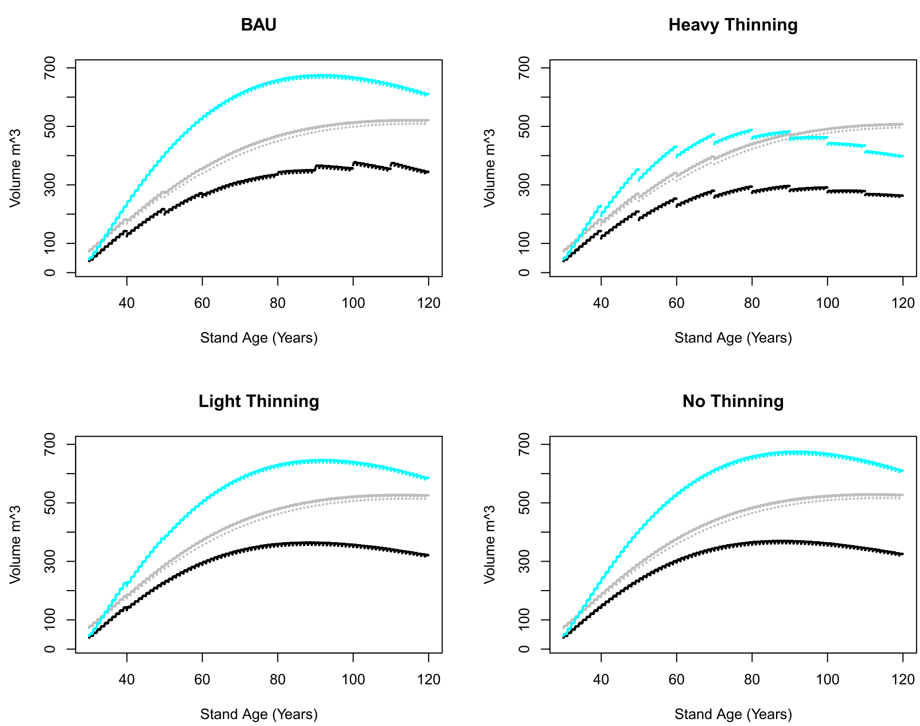

Fig. 6 The four regimes (BAU, heavy, light & no thin) compared when modified by storm damage for beech monoculture (black), spruce monoculture (blue) and beech/spruce mixture (grey). The *y*-axis shows the extracted volume, and the *x*-axis shows the stand age from 30 to 120 years old

highest risk at a given height is more associated with the no-thinning monoculture and mixed simulations, while the least risk at a given height tends towards the monoculture stands with intense thinning. The no-thin strategy in both monoculture and mix holds the higher level of risk. This is especially true for spruce, whereas

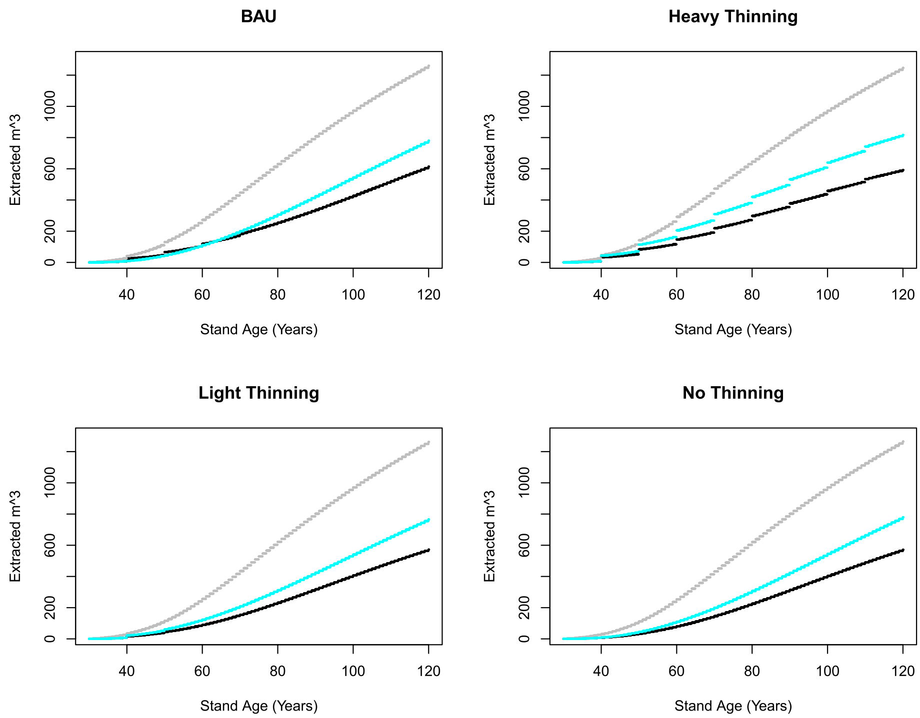

Fig. 7 The four regimes with their related extracted and salvaged volumes compared when modified by storm damage for beech monoculture (black), spruce monoculture (blue) and beech/spruce mixture (grey). The *y*-axis shows the extracted volume, and the *x*-axis shows the stand age from 30 to 120 years old

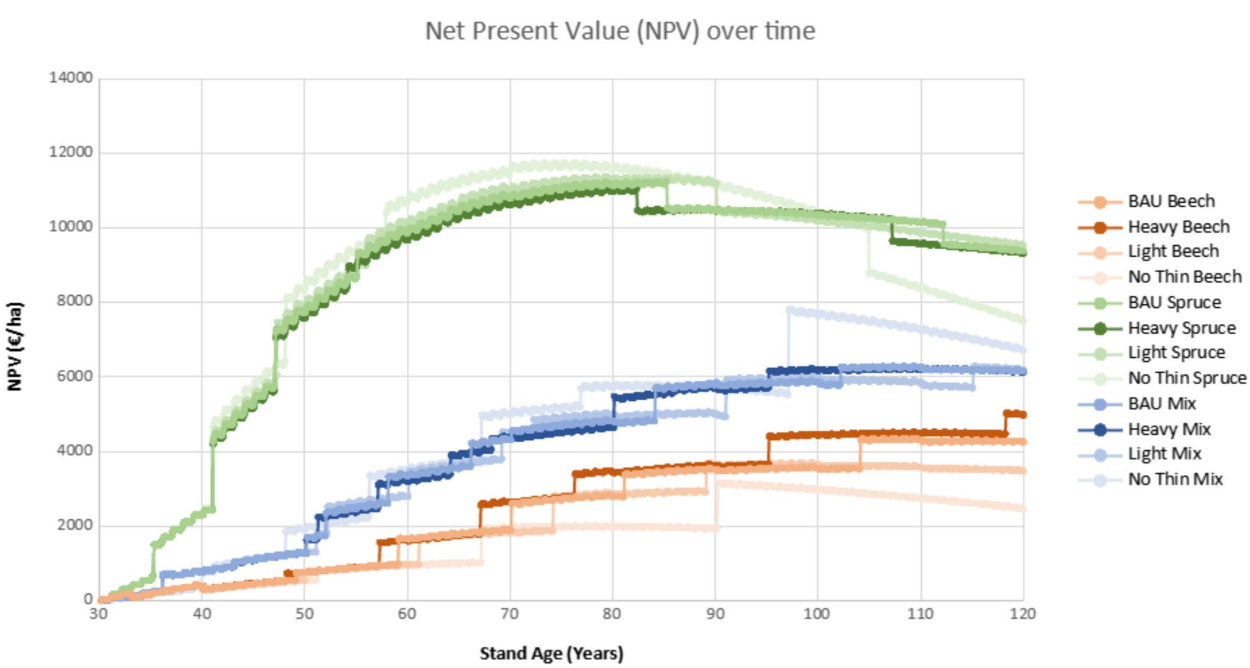

Fig. 8 Net present value (NPV, *y*-axis) in €/ha progression over time (stand age, *x*-axis) for spruce monoculture (green), beech monoculture (orange) and beech/spruce mixture (blue), considering BAU, intensive and light thinning and a no-thin regime. Large vertical jumps in the NPV represent where a higher value diameter class has been reached

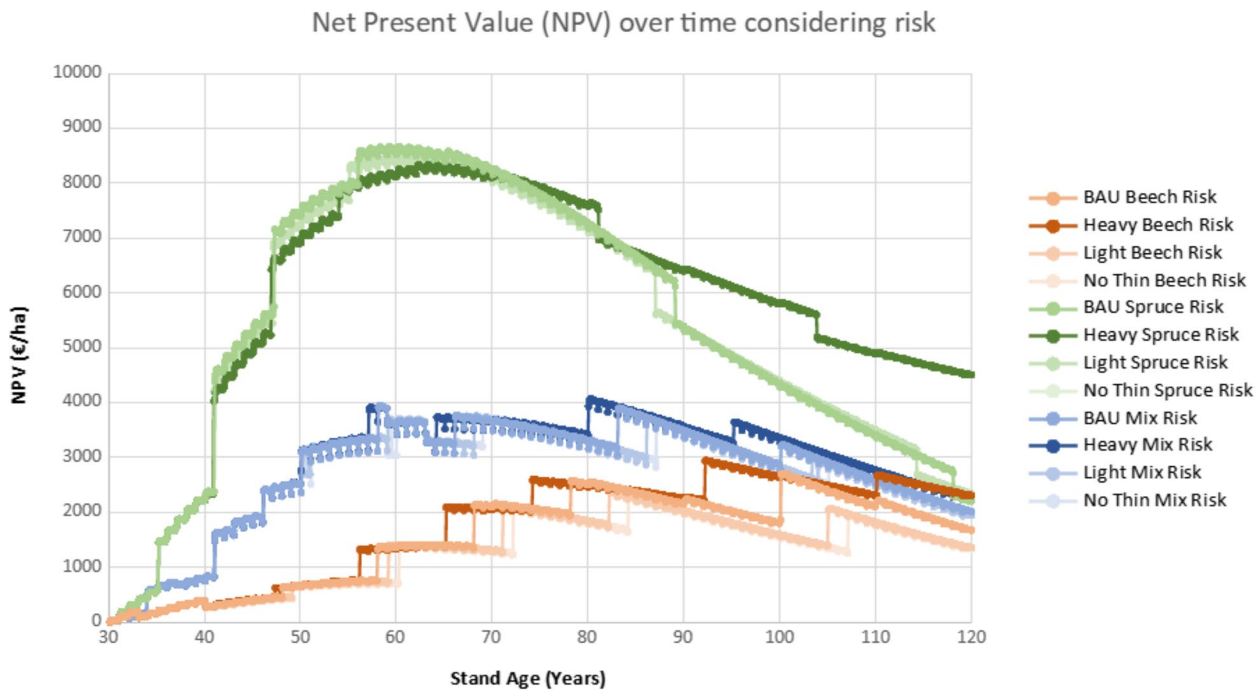

Fig. 9 NPV (*y*-axis) progression over time (*x*-axis) for spruce monoculture (green), beech monoculture (orange) and beech/spruce mixture (blue), considering BAU, intensive and light thinning and a no-thin regime, where stems are removed based on storm damage risk. Large vertical jumps in the NPV represent where a higher value diameter class has been reached. Sharp drops in the NPV indicate where storm risk has removed stand volume

in both cases, the heavy thinning strategy has an overall lower risk level. It is also clear that at a relative height, the wind damage susceptibility of spruce is far higher than of beech. In addition, the degree of increase in risk with height increase is much more pronounced in spruce than it is in beech. In Appendix Fig. 27, it can also be seen that, while that there is a difference between the risk level of beech in mixture and monoculture at a given height, the management strategy used plays a more decisive role in differentiating the risk level. Intensive thinning yields the lowest risk in this case, while light thinning yields the highest risk of the thinning regimes. However, when observing the same figure, we see that beech mixed compared with beech monoculture has uniformly the lowest risk when an intensive thinning is applied.

In Fig. 6, the total volume of high thin is virtually identical to the monoculture until 120 years old. For the no-thin regime and BAU, the spruce monoculture had the highest end volume at 611 m^3 ha^{-1}. The extracted and storm volume of the same stand are shown in Fig. 7, and considering storm damage risk, from the examples analysed, spruce monoculture manages to perform better than beech or mixture in all thinning strategies, except under heavy thinning. When considering extracted volume however, mixed regimes perform better in terms of volume, while monoculture has less extracted volume.

In Fig. 7, mixture also had the highest level of salvaged and extracted volume in all cases. Due to effect of volume removed by the effect of storm damage, a large amount of volume is removed in the no-thin regime also. Here, the mixed strategies emerge with the highest volume extraction in all strategies. Heavily thinned spruce has the second highest volume at the end of 120 years.

3.3 Economic evaluation

In Fig. 8, beech and spruce monoculture are compared with a 50/50 mixture of spruce and beech with the same total stem number, as was the case for the no-risk volume projections above. Spruce is a very favourable option in this case, as even though its value declines after ~ 80 years, it stays the most profitable species until the end. The mixture is the middle-ground strategy. We see that beech is the least desirable species and remains the least profitable throughout. The least profitable scenario overall was the no-thin beech monoculture, which has the lowest NPV at every point in the rotation part.

Figure 9 shows net present value per hectare versus stand age, where volume is modified by risk and the NPV values relate to the risk-modified volume projections shown above. Spruce is the most profitable management strategy, reaching 8600 € ha^{-1} by 57 years. However, this strategy then rapidly declines until the end of the rotation. The mixed strategies maintain a more middle-ground status, whereby in the former part of the rotation it is more profitable than beech but less profitable that spruce. Then, the profitability becomes less species specific and is more defined by the management.

Comparing Figs. 8 with 9, spruce has a similar progression in NPV in both cases, until ~ 60 years, but continues to increase when not considering risk and begins to decrease after this point when considering risk. The maximum NPV reached when risk is not considered is ~ 11,100 € ha^{-1} at 70 years old for the light thinning spruce monoculture. When risk is considered, the highest NPV value achieved was ~ 8600 € ha^{-1} for no-thin spruce at ~ 58 years old. At the end of the 120 years when not considering risk, light thinning spruce was the most profitable at 9517 € ha^{-}1, while no-thin beech monoculture was the least profitable at 2445 € ha^{-1}. Considering wind damage risk, the least profitable thinning strategy at 120 years was the no-thin beech monoculture at 1328 € ha^{-1}, and the most profitable was the heavily thinned spruce monoculture at ~ 4508 € ha^{-1}. In the risk-modified NPV estimation, by the end of the rotation, almost all strategies converge to a similar range of values, i.e. between 1500 and 2500 € ha^{-1}. The notable exceptions to these are the light and no-thin beech strategies, which are lower, and the heavily thinned spruce, which is distinctly above the other strategies. In the no-risk simulations, spruce was favoured for the entirety of the rotation. Overall, although spruce in the former part and beech in the latter part are most profitable, the mixture is both relatively profitable in the former and latter part of the rotation.

When comparing these species using the statistical tests in Appendix Table 5, there is no significant difference between these species' storm damage risk. Additionally, in Appendix Table 6 when comparing the storm damage risk (*P*-value) in terms of soil fertility, soil–water capacity and soil type, there were no significant differences.

4 Discussion

4.1 Calibration and stand growth estimation

The DBH calculations for spruce, pine, oak and Beech showed a general improvement in comparison with the prior parameter set, following the calibration. Given the heterogeneity of the WETs, the bias ranges remain within a level which is satisfactory to the intended purpose of the parameterisation. Compared with other calibrations of European tree species in Germany and other Central European countries (e.g. Forrester et al. 2021, Augstynczik et al., 2017, Nölte et al. 2020), our results consider the wide geographical range for which we had to calibrate. In the case of validation, the range of values however are wider, especially for the BA of Douglas fir and pine. However, as seen in Table 1, while DBH and height remained low (under 15% PBias), for BA and volume, the figures were generally higher, the volume of larch being the most extreme value. Therefore, we must take these bias uncertainties into consideration when interpreting growth projections. This would apply to, for example Fig. 4, where the standard deviation shown in Table 1 would indicate that especially beech has a higher uncertainty in the volume parameter estimation; therefore, beech monocultures in mixture or monoculture could have greater volume, since the parameter was generally underestimated in the validation (see Table 1 & Appendix Fig. 18).

Yield is defined as the entire stand biomass from stand establishment. A direct positive mixing effect is assumed when the mixed-stand productivity is greater than the productivity of the two pure stands of similar size (ordinary overyielding) or when the mixed-stand productivity even exceeds the sum productivity of pure stands of species 1 and 2 (transgressive overyielding). In contrast, underyielding means that the productivity of the mixed stand is less than that of the pure stands (Pretzsch 2009). When mixing Norway spruce and silver fir, Huber et al. (2014) found that, on sites studied in Switzerland, the mixture of these species resulted in underyielding, although this was somewhat dependent on-site factors. Vallet and Perot (2011) obtained results indicating that silver fir growth was enhanced in mixture, while Norway spruce's growth remained unchanged. In our case, the comparison of monocultural and mixed stands in Fig. 3 showed that the volume growth of the mixed stand underyielded in the thinned scenarios, since the total volume just slightly increased compared to beech monoculture but ~ 300 m^3 less than that of spruce monoculture. In contrast, the mixed-stand overyields by the end of rotation period, since it is closer to the volume of the spruce monoculture than to the beech monoculture. Toigo et al. (2015) made a comparison of several European species in various mixture combinations, specifically beech/spruce, eech/Fir, Fir/Spruce, Oak/Pine and Beech/Oak, which showed growth gains especially for beech, fir and oak in mixture over monoculture. Additionally, Pretzsch et al. (2013) obtained differing mixture effects for beech and oak, depending on site quality. They found that on high-quality sites, the overall growth of beech and oak was reduced to a small degree. In our case, the growth of oak/beech mixed stands (e.g. Appendix, Fig. 26) showed a very small difference in volume comparing with beech monoculture. Sterba et al. (2018) found that spruce mixed with larch caused a large decrease in the growth of larch, while the spruce can underyield in the earlier part of the rotation, it then over-yields in the latter part. In our case, overall, the spruce/larch mixture yielded slightly under the spruce monoculture in Appendix Figs. 20, 22, 24 and 26.

4.2 Damage risk estimation and growth projections, modified by damage probability

Spruce displays a lower risk than Douglas fir for the first 80 years (approx.), but after this point, the damage risk of spruce is greater than Douglas fir (Fig. 5). Douglas fir and spruce have far higher overall storm damage risk than the other species, in agreement with Albrecht et al. (2013), where it was found that Douglas fir and Norway spruce have a similar level of damage probability. This difference would be due to the sensitivity of the model to changes in the height, as well as the relative influence of the height and diameter ratio (Schmidt et al. 2010). Schelhass (2008) found that low height-diameter ratios were most effective in avoiding damage, and in the case of Douglas fir, this ratio could be improved when mixed with beech, and Albrecht et al. (2012) found that, although Norway spruce and Douglas fir have high economic value, this value is also counterbalanced by their relatively high risk of storm damage. Albrecht et al. (2015) found that intensified management reduced the damage risk of silver fir (and Norway spruce). Suvanto (2018) modelled storm risk for Norway spruce and Scots pine and found that these species had higher damage risks than broadleaf species. Scots pine in Fig. 5 begins with a higher storm damage risk than beech until about year 80 but then remains relatively constant, and so pine has a lower damage risk in the latter part of the rotation.

As seen by the risk-modified beech and spruce mixture, the beech monoculture performs the best, with the mixture either performing as well, but with a shorter rotation, or has an inferior performance. Clearly, when volume growth in beech monoculture and in mixture with pine (Appendix, Fig. 22) is modified by risk, the volume growth progression of the stand mirrors that of beech monoculture quite closely. However, this also results in a reduced rotation length. This is not the case where no thinning takes place, but there is then no intermediate timber harvesting. However, the no-thinning strategy sees the stand least affected by damage risk, and therefore, factors, such as the extracted volume and implied rotation length, will need to be considered in choosing the most appropriate strategy involving risk.

4.3 Economic evaluation of management strategies and mixtures

With regard to spruce monocultures, for Samariks et al. (2020), changes in spruce management, involving timely precommercial thinning and lower planting density, can ensure positive net present value and is most beneficial in areas of high wind risk. In addition, spruce need not be changed as the dominant commercial species. The case for lower density and active thinning is supported in our simulation study, where later in the rotation the difference of more and less intensively managed spruce becomes more apparent when considering wind damage risk and by year 120, with a difference in value of ~ 2500 € ha^{-1}.

In Griess and Knoke (2013), it was found that the highest net present value for stands affected by risk contained a high proportion of spruce and low proportion of beech. This was due to a reduced risk level. They found that a near 50/50 mixture of spruce and beech resulted in a lower net present value than spruce monoculture. However, the standard deviation of the net present value was reduced in this case. In our analysis, while we only consider 50/50 mixtures, we see that the management strategies in mixture do not experience a large deviation from one another. Our results are consistent with the finding that mixed stands have a lower net present value under risk, as seen in Fig. 9. However, at its most profitable, spruce monoculture is ~ 4500 € ha^{-1} more profitable than the 50/50 mixture at 55–60 years old. This serves as an argument for the profitability of shorter rotation spruce monocultures under wind damage risk. Also, Knoke et al. (2005) advised that risk-averse forest owners should establish spruce stands where 10–15% is beech admixture. Also, when salvage logging is not undertaken in the aftermath of a storm, there are no large negative economic impact and provide an additional benefit to biodiversity (Knoke et al. 2021).

We recognise that earlier studies, such as Pellikka and Järvaenpää (2003), found that thinning could contribute to storm damage. However, given the greater diameter growth allowed by heavy thinning, our study indicates that this itself can be a mitigation factor which can counteract the effect of canopy openings. A study could be made of different thinning timings to find an optimal timing to mitigate damage effects. In addition, the calculated damage risk depends on the growth characteristics of specific species in the region in which it is calibrated for, so the risk characteristics may change in different regions. Another aspect of our results is that, even if the net present value still remains high, damage risk can still be quite high while the high value and usable volume of spruce compensates for the damage risk. It also depends on the degree of projected climate change effects of tree species growth, as projected in Dyderski et al. (2017), but with future climate data, the model can reproduce these effects in a subsequent study.

Neuner and Knoke (2017) found that spruce monocultures' annuities decline under climate change, although beech admixture mitigates this loss, and with low proportions of beech, the revenue is similar to spruce monoculture but with reduced risk caused by warmer, drier climate. Although we do not consider climate change in this study, we see that spruce/beech mixtures earn less than spruce, although the mixed species strategies' profitability remains more constant, although less profitable.

While 3-PG mix can be calibrated for local climatic conditions and for the growth parameters of particular species in a given region, the Lothar model is a statistical model, based specifically on storm damage data within Germany. Therefore, while the specific model may not be transferrable outside of its intended region of use, another localised wind damage risk model could be utilised in its placed, assuming that its inputs and outputs are compatible with 3-PG. In addition, since the 3-PG model is primarily intended for use in relation to managed forests, it of itself does not have the capability to reproduce the complexity of a natural forest. For this task, an individual tree model could better represent these complexities in such areas as high age, diameter and species heterogeneity, as well as gap dynamics, which are not represented in a stand-level model such as 3-PG. In the case of the Lothar model, the model could still have relevance in unmanaged German forests, since it can be implemented at the individual tree level.

5 Conclusion

The species parameters provide a basis for a projection of seven tree species in future forest conditions and, in turn, the projection of future wind storm damage in German forests. In the calibration, each species showed differing levels of bias and deviation in the outputs. Nevertheless, validation of monoculture and mixed stand data allowed for the successful simulation of height, DBH, BA and volume.

We may also conclude, according to these modelling results, that the species, mixture and management affecting the stand density have an impact on storm damage susceptibility of a forest stand. Intensive thinning generally reduced the risk at a given height, and mixture also reduced risk.

We conclude that heavily thinned spruce stands are the most profitable under storm risk, but spruce monocultures also experienced the sharpest decline in value during the considered period. When other risks like drought, which has become a major source of stress for European forests in recent years and likely in the coming decades (Gazol and Camarero 2022), or insects are included, these factors could lead to different conclusions as to the most profitable strategy.

This modelling experiment provides the basis for a wider study on the susceptibility of various stand types to wind risk and, in turn, enables a visible differentiation between the best strategies when only considering timber production and those also considering wind damage risk. However, given that forests are often required to achieve multiple objectives, notably nature protection value and carbon sequestration, the methodology could also be extended to include these factors under climate change scenarios.

Appendix 1

Glossary

Table 2 Glossary of abbreviations

Abbreviation	Full name
BAU	Business as usual
3-PG	Physiological principles in predicting growth
FVA-NW	"Nordwestdeutsche Forstliche Versuchsanstalt" — North-West German Forestry Research Institute
FVA-BW	"Forstliche Versuchs- und Forschungsanstalt Baden-Württemberg" — Forestry Research Institute Baden-Württemberg
Forst-BW	"Forst Baden-Württemberg" — Forest Baden-Württemberg
WET	"Wald Entwicklungstyp" — forest development type
DBH	Diameter at breast height
BA	Basal area
DWD	"Deutsche Wetter Dienst" — German Weather Service
PBias	Percentage bias

Appendix 2

Methods

Calibration inputs

Growth Regions: In our modelling approach, the transects were separated into segments, corresponding to the German "Wuchsgebiete" (Growth Regions), each of which displays unique environmental attributes, contributing to the growth properties within the region. The growth regions used in the calibration corresponded to the endpoints and intersections of the transects, as well as two additional regions in central Germany. This was to ensure that the variation in conditions within Germany could be accounted for.

Climate: In order to run the model, monthly location-based climate data of temperature, precipitation and frost days were utilised, which were provided by the Environmental Meteorological Institute in University of Freiburg. The monthly solar radiation input was provided by the DWD historical database (see References).

Stand: Every age class was initialised with starting values for DBH, Height and Basal Area corresponding to a plot in the growth region in question. In the model initialisation starting values for stem, foliage and root biomass are required. In order to calculate these values generalised allometric equations (Forrester et al. 2017) were applied to calculate the related stand biomass of the stems, foliage and roots. These calculations were primarily based on stand mean DBH but additionally the stand basal area and/or stand age, depending on the species. In some cases where the specific species equations did not yield results corresponding to the initial values of the specific age class, general equations for conifer or broadleaf trees were chosen, or indeed, from another species, if it yielded a better fit to the initial biomass values. These are shown in Table 3.

To aid in the understanding of the diameter, stem density and age class ranges used to parameterise the tree species Figs. 10, 11, 12, 13, 14, 15 and 16 provide a guideline to these relationships.

Table 3 The utilised biomass equations from Forrester et al. (2017) for each calibrated tree species

	Foliage	Root	Stem
Beech	Beech	Beech	Beech
Douglas fir	Larch	General Conifer	Larch
Silver fir	General Conifer	General Conifer	Silver fir
Larch	Larch	General Conifer	Larch
Oak	Oak	Oak	Oak
Pine	Larch	General Conifer	Larch
Spruce	Spruce	Spruce	Spruce

Calibration process

The first step of the calibration was to vary the parameters manually until an approximate fit within the initial parameter ranges (from Forrester et al. 2021) was reached. These were then utilised as the starting parameters for the Bayesian calibration. The parameters were then permitted a $\pm$ 15% range of variation, given that the chosen parameters have a large effect on the model outputs. In the case of highly sensitive parameters, e.g. the constant and power controlling the DBH scaling based on the stem mass, these parameters were varied at range of $\pm$ 0.010. In Bayesian calibration the initial parameter set is varied by comparing with a measured or empirical dataset using a likelihood function. The likelihood function determines the probability of the parameters generating the same data as the empirical dataset. Using Markov Monte Carlo Chains the model runs over a given number of iterations, to evaluate the most probable parameter values to generate the same output values as the calibration data. For this calibration we specified 1250 iterations in two chains to give a total of 2500 iterations. Subsequently an output parameter set, a posterior, provides updated parameter values with narrower parameter uncertainty ranges, which provide a better fit of the desired outputs to a given region.

The calibration was carried out using the R package "Bayesian Tools". In the cases where linear models needed to be calibrated, e.g. for height function calibration, the linear model calibrations were carried out using the nls function in base R.

Appendix 3

Posterior validation

The final step was to validate the derived parameter in mixed stands. In both cases PBias were used as comparative metrics for the validation. Plots in Baden Württemberg were utilised to evaluate the efficacy of the derived parameters, partially from the FVA-BW and partially from Forst-BW. The FVA-BW plots utilized climate data from the nearest weather stations, while in the case of the Forst-BW plots the weather data was the same as

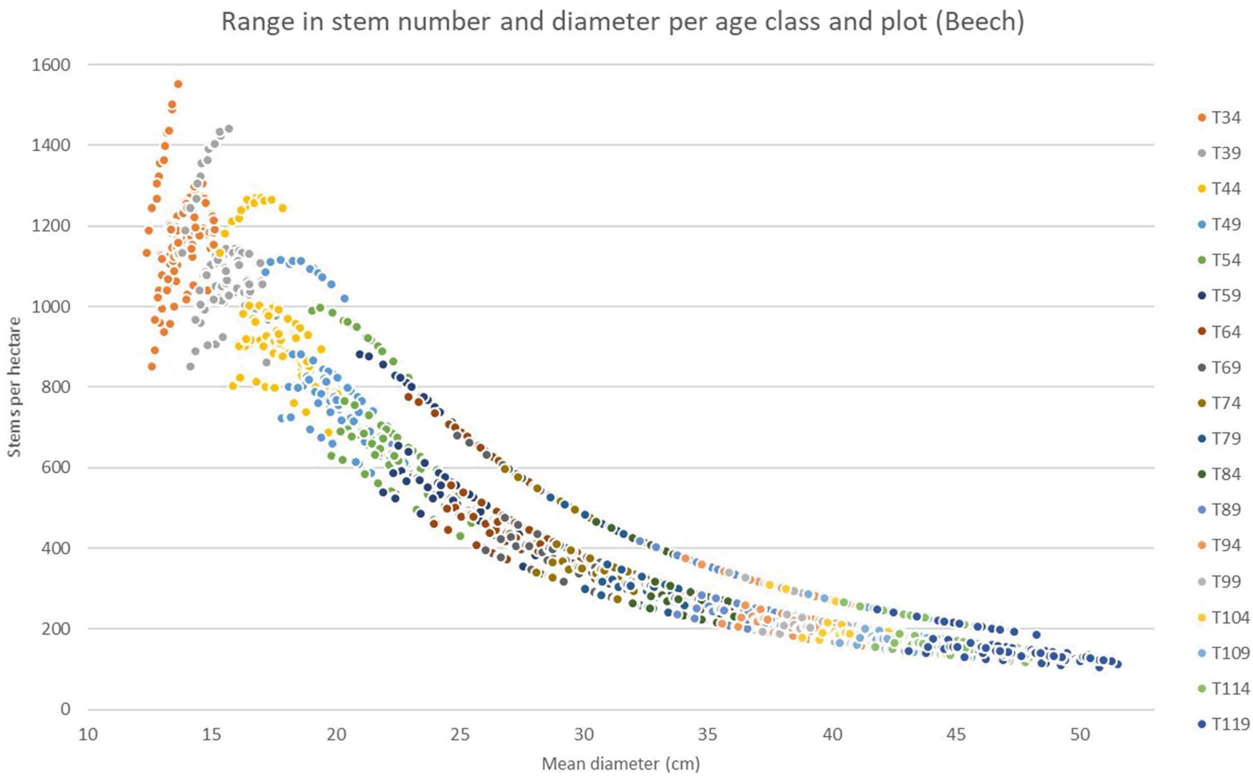

Fig. 10 Stems per hectare (*y*-axis) versus mean diameter (*x*-axis) for the data utilised to calibrate beech. The colours of the points correspond to density/diameter relationships of particular age classes. The legend shows the number in years for the given age class

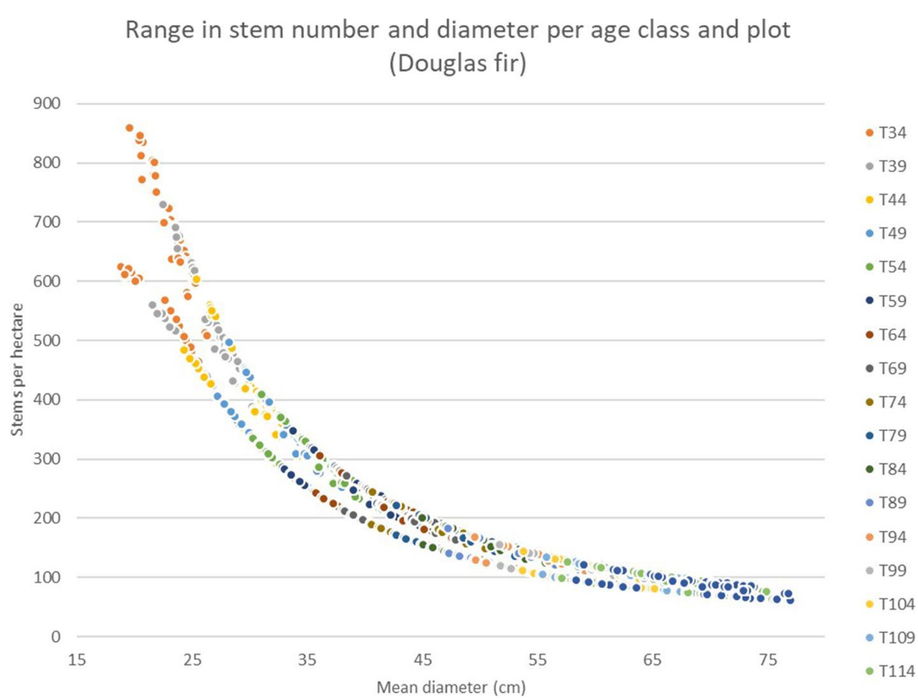

Fig. 11 Stems per hectare (*y*-axis) versus mean diameter (*x*-axis) for the data utilised to calibrate Douglas fir. The colours of the points correspond to density/diameter relationships of particular age classes. The legend shows the number in years for the given age class

Fig. 12 Stems per hectare (*y*-axis) versus mean diameter (*x*-axis) for the data utilised to calibrate Silver fir. The colours of the points correspond to density/diameter relationships of particular age classes. The legend shows the number in years for the given age class

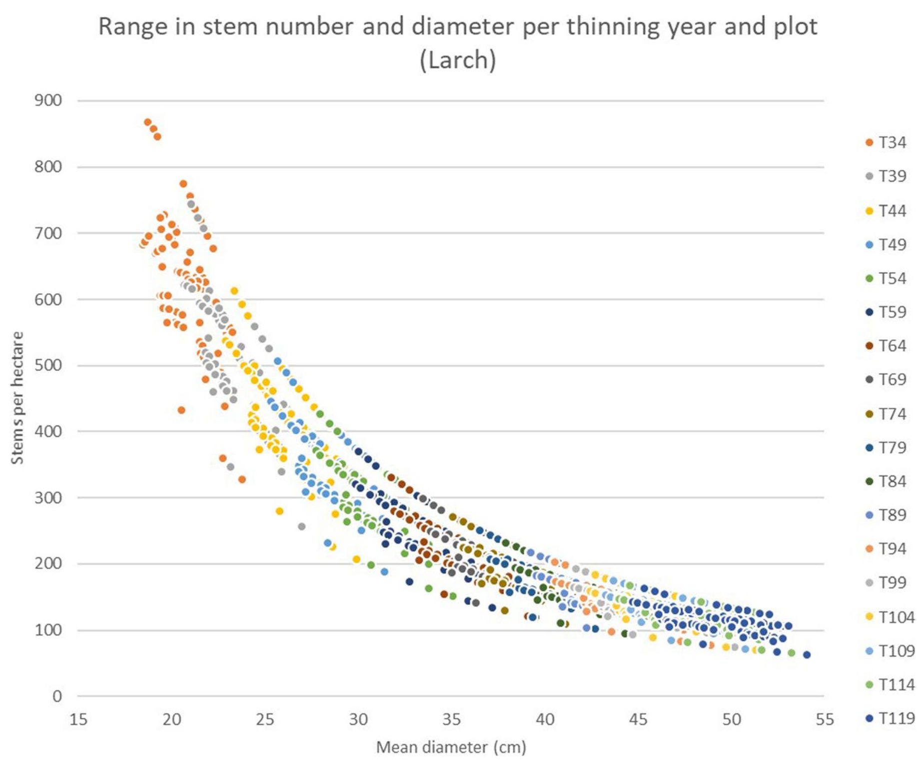

Fig. 13 The above shows stems per hectare (*y*-axis) versus mean diameter (*x*-axis) for the data utilised to calibrate larch. The colours of the points correspond to density/diameter relationships of particular age classes. The legend shows the number in years for the given age class

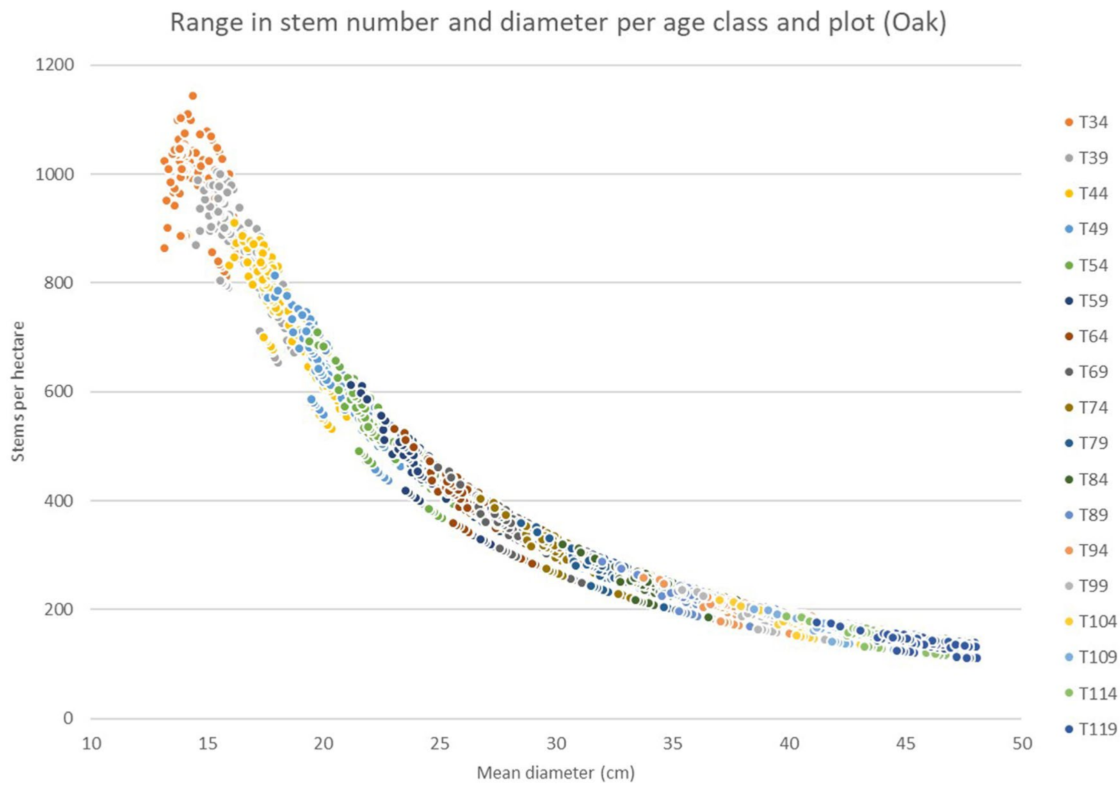

Fig. 14 The above shows stems per hectare (*y*-axis) versus mean diameter (*x*-axis) for the data utilised to calibrate oak. The colours of the points correspond to density/diameter relationships of particular age classes. The legend shows the number in years for the given age class

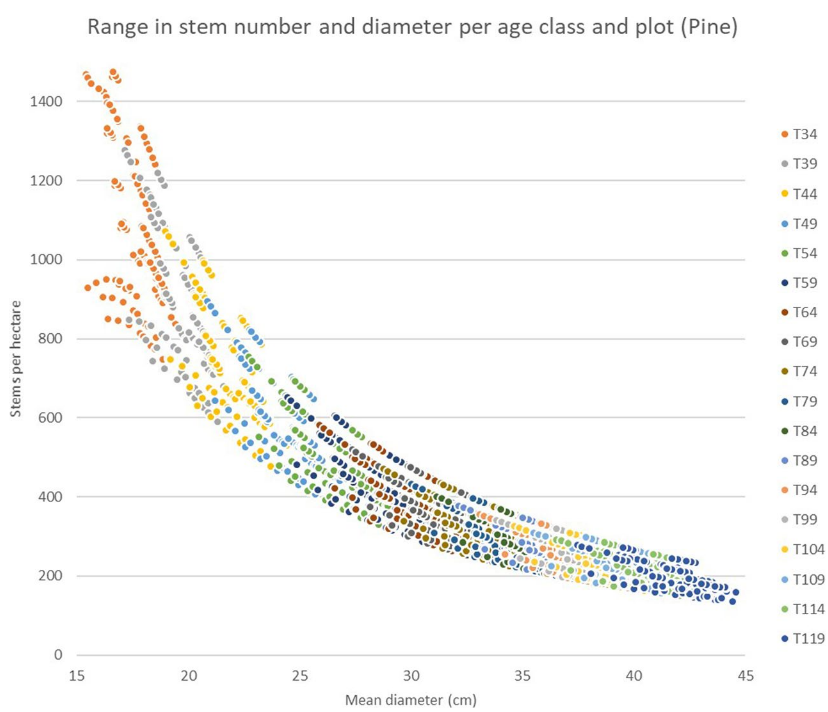

Fig. 15 The above shows stems per hectare (*y*-axis) versus mean diameter (*x*-axis) for the data utilised to calibrate pine. The colours of the points correspond to density/diameter relationships of particular age classes. The legend shows the number in years for the given age class

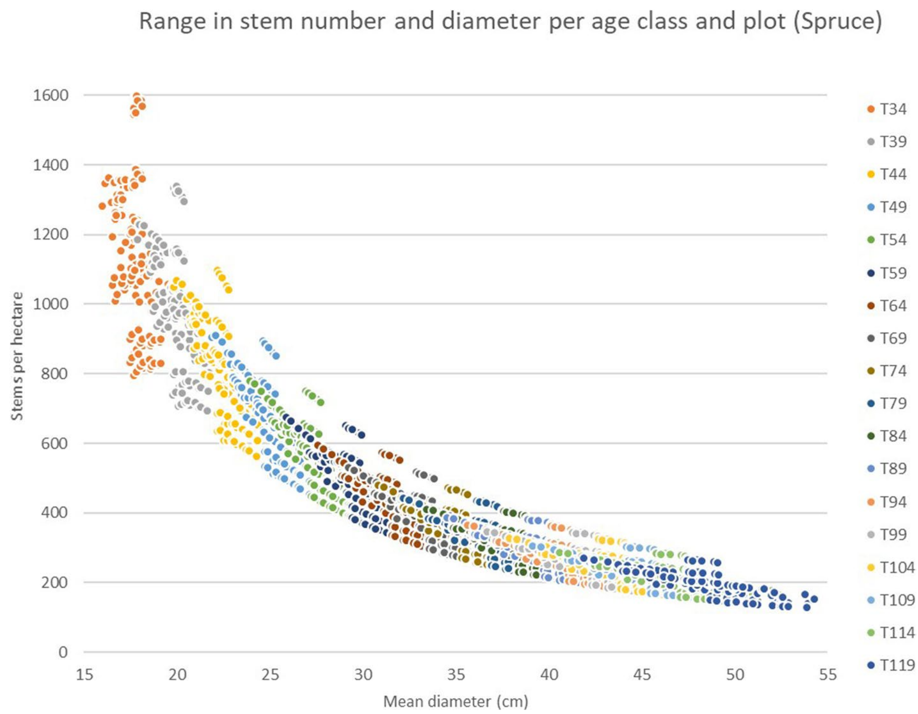

Fig. 16 The above shows stems per hectare (*y*-axis) versus mean diameter (*x*-axis) for the data utilised to calibrate spruce. The colours of the points correspond to density/diameter relationships of particular age classes. The legend shows the number in years for the given age class

was used in the monoculture calibrations i.e. maximum and minimum temperature per month, mean monthly precipitation and mean total frost days per month. The mean monthly solar radiation was extracted from the mean monthly solar radiation in relation to the sample point's location. Mean DBH, Height, Basal Area and Volume metrics were the units of comparison for the FVA-BW and Forst-BW plots. Stem number per hectare was provided in the stand data from the FVA-BW and in the case of the Forst-BW plots stems per hectare were derived from the number of stems per plot which were over 15 cm and were then extrapolated to the per hectare level. The number of inventory samples varied between the FVA plots but for the Forst-BW plots, while the sampling years varied, there were for each sample point three measurements of DBH, Height, Volume and Basal Area. For the Forst-BW plots, each tree had a calculated volume (m3) and the mean value of the measured trees was multiplied by the stems per hectare. For the Basal Area the derived mean DBH was also converted to Basal Area per hectare using the calculation $(DBH / 2 / 100)^2 * pi *$ stems/ha.

The tree biomass growth in the mixed stands from Baden Württemberg was then compared with monoculture stands with the same inputs for each species, in order to determine the degree of difference in the growth rate with and without mixture. To determine the degree of congruence between the 3-PG Mix modelled outputs and the calibration and validation age classes and stands, Percentage Bias (Pbias) was utilised.

In Fig. 17, the box plots show where the PBias values are most concentrated in the distribution, the central line in the box being the median value and the horizontal lines and points are the outliers to the distribution. The negative values on the x axis show where the model underestimates the calibration data and positive values are where the model overestimates. The narrower and closer the spread to the vertical zero line, the closer the modelled values are to the calibration data.

The derived parameters are shown in Table 4. Figures 17 and 18 show the distribution of the PBias of the species parameter calibration and validation respectively. To validate the simulations using the calibrated parameters, we compared mixed simulations with inventory stand data. Figure 17 shows the PBias of the "observed" versus simulated projections of BA, DBH and Height. In general, the median of the values remains less than 10%, and some less than 5%, with some exceptions. This is especially evident for the BA calculations for Spruce, Pine and Beech.

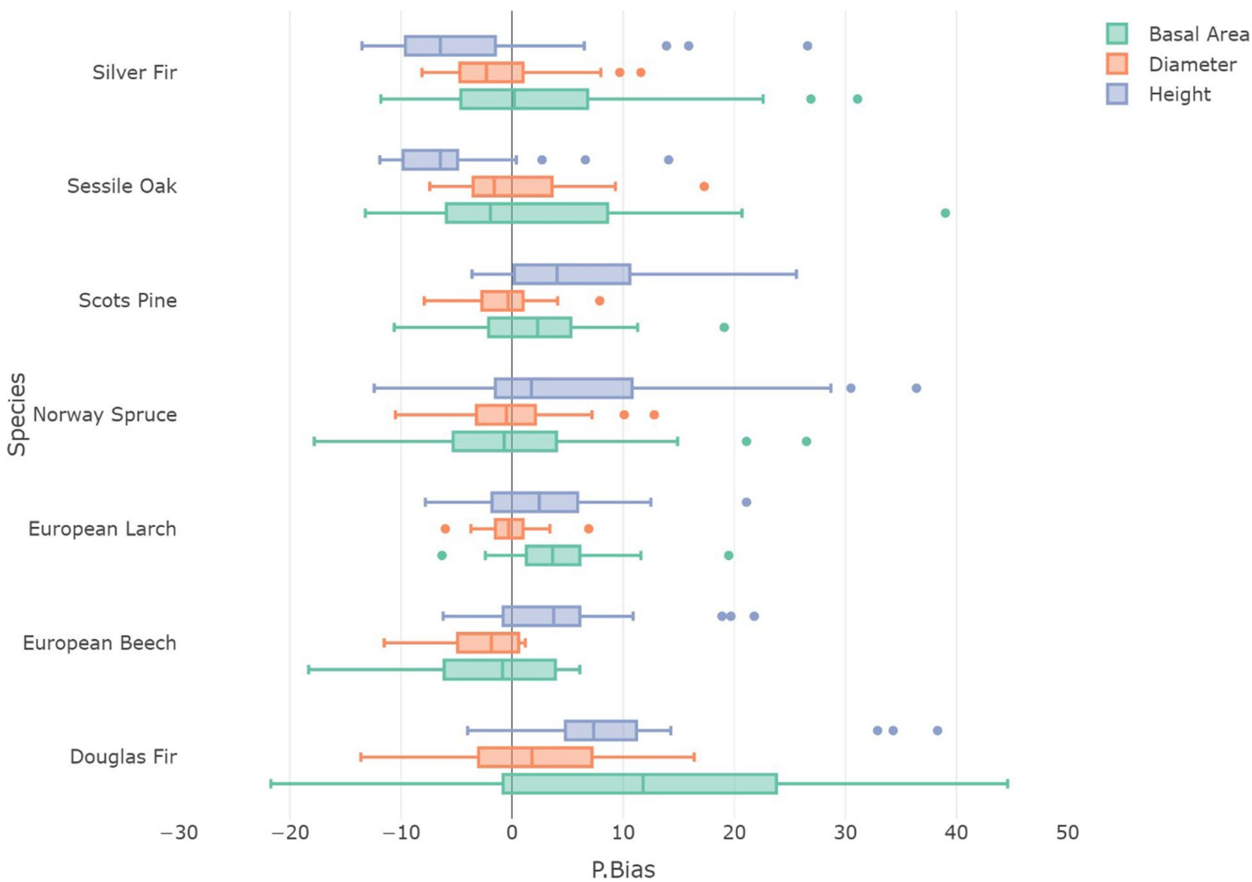

Fig. 17 The Pbias (*x*-axis (%)) values in the calibration of the named tree species (*y*-axis) for basal area (green), diameter (orange) and height (blue)

For validation (Fig. 18) of the derived parameters, volume was also added to the output variables which were subject to a PBias comparison. In addition, a comparison of the prior parameters to the posterior parameters was carried out using the same statistical tests as were used for the validation of the parameters against stand data. For the most part, the derived posterior parameters show an improvement over the prior parameter distributions. The main exception to this was the case of height projections for Douglas fir. Douglas fir also did not show a clear improvement in terms of the BA calculation and the median value was 0%. This is in contrast to the BA statistics for beech and pine, as this was also the case for the diameter values of the same species, where all comparisons showed improvement in performance of the posterior over the prior. Larch and Fir showed a small improvement, e.g. median BA < 5%. The remaining species showed improvement in the performance of the posterior over the prior parameters.

In Fig. 19, for beech, DBH is highest when mixed with oak (84 cm) and with spruce (79 cm) at the end of the rotation. It is the most reduced when mixed with Douglas fir and Silver fir (29 cm and 26 cm respectively). For comparison, beech in monoculture reaches a DBH of 65 cm by the end of its rotation. In Fig. 20, the shortest turn-around time for the stand was 70 years old for the beech/scots pine mixture. The highest volume at the end of rotation was the beech/Douglas fir mixture (1005 m3) and the lowest was beech/pine (387 m3). For beech monoculture the end volume was 488 m3.

In Fig. 21, DBH is highest when beech is mixed with oak (80 cm) and with spruce (78 cm). It is the most reduced when mixed with Douglas fir and Silver fir (29 cm and 26 cm respectively). Beech in monoculture reaches a DBH of 72 cm by the end of the

Table 4 The table below shows the derived parameters for all seven calibrated species

Name	*Fagus sylvatica*	*Pseudotsuga menziesii*	*Abies alba*	*Larix decidua*	*Quercus petraea*	*Pinus sylvestris*	*Picea abies*
pFS2	0.073 (0.067–0.078)	0.242 (0.227–0.253)	0.5951	1.05 (0.888–1.174)	1.581 (1.391–1.750)	0.629 (0.551–0.709)	0.475 (0.352–0.562)
pFS20	0.013 (0.013–0.014)	0.225 (0.212–0.236)	0.262 (0.229–0.286)	0.017 (0.016–0.018)	0.029 (0.028–0.031)	0.067 (0.061–0.071)	0.063 (0.056–0.067)
aWS	0.084 (0.084–0.092)	0.098 (0.089–0.108)	0.083 (0.082–0.084)	0.125 (0.117–0.134)	0.072 (0.063–0.081)	0.124 (0.114–0.132)	0.042 (0.033–0.052)
nWS	2.493 (2.483–2.501)	2.356 (2.346–2.363)	2.343 (2.334–2.352)	2.314 (2.303–2.322)	2.46 (2.460–2.469)	2.316 (2.308–2.328)	2.428 (2.423–2.433)
pRx	0.602 (0.0.526–0.678)	0.519 (0.489–0.543)	0.769 (0.693–0.844)	0.727 (0.652–0.807)	0.352 (0.297–0.429)	0.656 (0.603–0.718)	1.096 (1.024–1.153)
pRn	0.054 (0.043–0.061)	0.132 (0.121–0.140)	0.206 (0.186–0.228)	0.053 (0.042–0.063)	0.062 (0.042–0.085)	0.282 (0.254–0.311)	0.261 (0.246–0.274)
gammaF1	0.004 (0.003–0.005)	0.016 (0.015–0.017)	0.002 (0.000–0.003)	0.03 (0.003–0.060)	0.021 (0.000–0.085)	0	0.002 (0.001–0.002)
gammaF0	0.001	0.007 (0.002–0.011)	0.001 (0.000–0.002)	0.001 (0.000–0.002)	0.026 (0.000–0.040)	0.000 (0.000–0.001)	0.014 (0.013–0.014)
tgammaF	60	60	60	0	0	60	60
gammaR	0	0.0001	0	0.0001	0.003	0.002 (0.001–0.002)	0.001
leafgrow	4	0	0	5	5	0	0
leaffall	11	0	0	11	11	0	0
Tmin	6.006 (5.717–6.261)	2.621 (1.761–3.214)	4.883 (3.561–6.133)	3.418 (3.029–3.735)	− 1.527 (− 2.801 to − 0.628)	− 4.994 (− 6.121 to − 4.061)	4.504 (4.440–4.548)
Topt	21.541 (21.039–21.951)	24.87 (24.153–25.707)	24.783 (23.536–26.075)	24.914 (24.008–25.654)	15.594 (14.345–16.805)	26.843 (25.599–28.045)	24.98 (24.887–25.092)
Tmax	30.7907	30.731 (28.558–32.310)	36.325 (34.293–38.113)	30.937 (29.250–32.874)	44.601 (42.559–46.455)	46.081 (43.717–47.456)	29.003 (28.731–29.342)
kF	1	1	1	1	1	1	1
fCalpha700	1.061 (1.010–1.120)	1.282 (1.225–1.335)	1.1966	1.078 (1.024–1.107)	1.1097	1.123 (1.108–1.141)	1.000 (0.991–1.009)
fCg700	0.8002	0.681 (0.613–0.759)	0.7069	0.731 (0.672–0.805)	0.8449	0.998 (0.941–1.055)	0.654 (0.614–0.708)
m0	0	0	0	0	0	0	0
fN0	0.6	0.6	0.6	0.6	0.6	0.6	0.4
fNn	1	1	1	1	1	1	1
MaxAge	199.106 (190.502–209.110)	148.731 (140.265–158.695)	550	650	725	600	251.772 (241.794–259.812)
nAge	4	4	4	4	4	4	4
rAge	0.924 (0.921–0.929)	0.95	0.95	0.95	0.95	0.95	0.95
gammaN1	0	0	0	0	0	0	0
gammaN0	0	0	0	0	0	0	0
tgammaN	0	0	0	0	0	0	0
ngammaN	1	1	1	1	1	1	1
wSx1000	291.770 (274.426–312.342)	213.3776	313.462	225.38 (214.614–235.938)	151.836 (148.025–155.695)	202.3125	378.3186
thinPower	1.447 (1.361–1.538)	1.5887	1.9777	1.983 (1.866–2.054)	1.836 (1.775–1.890)	1.6025	1.7732
mF	0.488	0.608	0.492	0.409	0.412	0.558	0.464
mR	0.436	0.563	0.446	0.312	0.373	0.48	0.391
mS	0.437	0.54	0.444	0.321	0.363	0.481	0.409
SLA0	24.72	6.56	12.32	13.83	18.49	4.29	8.71

Table 4 (continued)

Name	*Fagus sylvatica*	*Pseudotsuga menziesii*	*Abies alba*	*Larix decidua*	*Quercus petraea*	*Pinus sylvestris*	*Picea abies*
SLA1	19.4	5	5.85	11.72	14.62	4.29	3.85
tSLA	35	44.7	18.1	14.5	7.35	1	25.1
k	0.458 (0.435–0.483)	0.645 (0.612–0.668)	0.64 (0.597–0.686)	0.341 (0.335–0.349)	0.644 (0.620–0.673)	0.479 (0.455–0.493)	0.269 (0.232–0.315)
fullCanAge	3	3	3	3	3	3	3
MaxIntcptn	0.32 (0.306–0.331)	0.411 (0.392–0.422)	0.3385	0.146 (0.135–0.153)	0.139 (0.129–0.146)	0.414 (0.398–0.429)	0.265 (0.259–0.271)
LAImaxIntcptn	3	3	3	3	3	3	3
cVPD	5	5	5	5	5	5	5
alphaCx	0.036 (0.034–0.038)	0.05 (0.048–0.053)	0.026 (0.024–0.028)	0.061 (0.058–0.064)	0.032 (0.029–0.035)	0.03 (0.030–0.031)	0.031 (0.028–0.032)
Y	0.47	0.47	0.47	0.47	0.47	0.47	0.47
MinCond	0	0	0	0	0	0	0
MaxCond	0.017	0.029 (0.028–0.030)	0.021 (0.019–0.024)	0.014 (0.012–0.016)	0.0199	0.014 (0.013–0.014)	0.026
LAIgcx	3.33	3.33	3.33	3.33	3.33	3.33	3.33
CoeffCond	0.044 (0.041–0.046)	0.062 (0.060–0.065)	0.0908	0.084 (0.081–0.087)	0.0477	0.062 (0.059–0.066)	0.077 (0.074–0.080)
BLcond	0.2	0.2	0.2	0.2	0.2	0.2	0.2
RGcGw	0.66	0.66	0.66	0.66	0.66	0.66	0.66
D13CTissueDif	2	2	2	2	2	2	2
aFracDiffu	4.4	4.4	4.4	4.4	4.4	4.4	4.4
bFracRubi	27	27	27	27	27	27	27
fracBB0	0	0	0	0	0	0	0
fracBB1	0	0	0	0	0	0	0
tBB	0	0	0	0	0	0	0
rhoMin	0.4	0.44	0.37	0.5	0.58	0.37	0.44
rhoMax	0.4	0.44	0.37	0.5	0.58	0.37	0.44
tRho	1	1	1	1	1	1	1
aH	37.73	46.09	30.91	40.17	1.31	45.69	46.09
nHB	17.85	24.57	16.78	19.84	0.691	23.01	24.57
nHC	0.00636	0.00576	0.00925	0.00398	0.1	0	0.00576
aV	0.000115	0.000139	0.000128	0.000047	0.000031	0.000118	0.000139
nVB	2.31	2.04	1.92	1.53	2	2.05	2.04
nVH	0.33	0.54	0.75	1.43	1.05	0.58	0.54
nVBH	0	0	0	0	0	0	0
Crown shape	3	3	3	3	3	3	3
aK	0.43	0.65	0.83	0.66	0.31	0.65	0.63
nKB	0.73	0.69	0.53	0.72	1.03	0.83	0.64
nKH	0	0	0	0	0	0	0
nKC	0.122	− 0.037	0	− 0.14	− 0.15	− 0.267	− 0.069
nKrh	− 0.126	0.196	0	0.248	0	− 0.087	0.067
aHL	23.32	21.18	24.93	27.97	20.13	11.77	35.18
nHLB	14.95	24.73	25.09	28.73	19.05	17.01	27.18
nHLL	0	0	0	0	0	0	0
nHLC	0	0.002	− 0.002	− 0.002	0	0	− 0.005
nHLrh	0	0	0	0	0	0	0
Dscale0	− 2.439	− 1.568	− 2.052	− 1.624	− 0.861	− 1.049	− 2.023
DscaleB	1.008	1.982	1.077	1.235	0.958	0.801	1.136
Dscalerh	0.21	0.055	0.757	0	0	0	0.051

Table 4 (continued)

Name	*Fagus sylvatica*	*Pseudotsuga menziesii*	*Abies alba*	*Larix decidua*	*Quercus petraea*	*Pinus sylvestris*	*Picea abies*
Dscalet	0.187	−0.902	0	−0.237	0	0.108	−0.049
DscaleC	0.295	0.395	0.403	0.435	0	0.186	0.382
Dshape0	0.491	0.985	−0.13	−0.109	−0.792	−0.689	0.328
DshapeB	0.345	0	0.228	0.481	0	0.372	0.562
Dshaperh	0.701	0	0.777	0.639	0	0	0.037
Dshapet	−0.138	0	0	−0.195	0	0	−0.254
DshapeC	−0.128	−0.073	0	0	0.583	0.111	−0.117
Dlocation0	0.723	0.284	0.462	0.293	0.444	0.129	0.391
DlocationB	0.87	−0.241	0.825	0.874	1.014	1.057	0.847
Dlocationrh	0	0.065	0	0	0	0	−0.004
Dlocationt	−0.138	0.944	0	0	0	−0.158	−0.001
DlocationC	−0.111	−0.152	−0.2	−0.224	0	−0.103	−0.187
wsscale0	−3.508	−3.454	−3.118	−2.768	−2.438	−2.905	−3.366
wsscaleB	2.445	2.447	2.384	2.461	2.606	2.081	2.369
wsscalerh	0.401	0.118	1.255	0.114	0	0	0.222
wsscalet	0.174	0	0	−0.192	0	−0.026	−0.033
wsscaleC	0.155	0.572	0.353	0.239	0	0.671	0.402
wsshape0	0.551	0.323	0.46	−0.491	−1.287	−0.404	0.16
wsshapeB	0.288	1.369	0.107	0.489	0.553	0.405	0.461
wsshaperh	0.585	0	0.705	0.428	0	0	0.273
wsshapet	−0.158	−1.263	0	−0.19	0	−0.098	−0.241
wsshapeC	−0.188	0	−0.196	0	0	0	−0.085
wslocation0	−0.081	−0.854	−0.168	−1.092	−0.966	−2.999	−0.937
wslocationB	1.915	−0.126	1.555	1.88	1.651	2.564	2.005
wslocationrh	−0.795	0.112	0	0	0	−1.081	−0.735
wslocationt	−0.483	1.971	0	0	0	−0.387	−0.228
wslocationC	−0.1	−0.609	−0.282	−0.469	0	0.291	−0.194

rotation. In Fig. 22, the shortest turn-around time for the stand was 70 years old for the beech/Scots pine mixture. The highest volume at the end was the beech/Douglas fir mixture (839 m3) and the lowest was / (332 m3). For beech monoculture the end volume was 368 m3.

In Fig. 23, DBH is highest when beech is mixed with oak (73 cm) and with spruce (71 cm). It is the most reduced when mixed with Douglas fir and Silver fir (34 cm and 27 cm respectively). Beech in monoculture reaches a DBH of 58 cm. In Fig. 24, the shortest turn-around time for the stand was 80 years old for the beech/Scots pine mixture. The highest volume at the end of rotation was the beech/Douglas fir mixture (1143 m3) and the lowest was beech/Silver fir (448 m3). For beech monoculture the end volume was 697 m3.

In Fig. 25, DBH is highest when mixed with oak (59 cm) and with spruce (59 cm) at the end of the rotation. It is the most reduced when mixed with Douglas fir and Silver fir (31 cm and 23 cm respectively). Beech in monoculture reaches a DBH of 50 cm by the end of the rotation. In Fig. 26, the highest volume at the end of the rotation was the beech/Douglas fir mixture (2012 m3) and the lowest was beech/Silver fir (1054 m3). For beech monoculture end volume was 1190 m3.

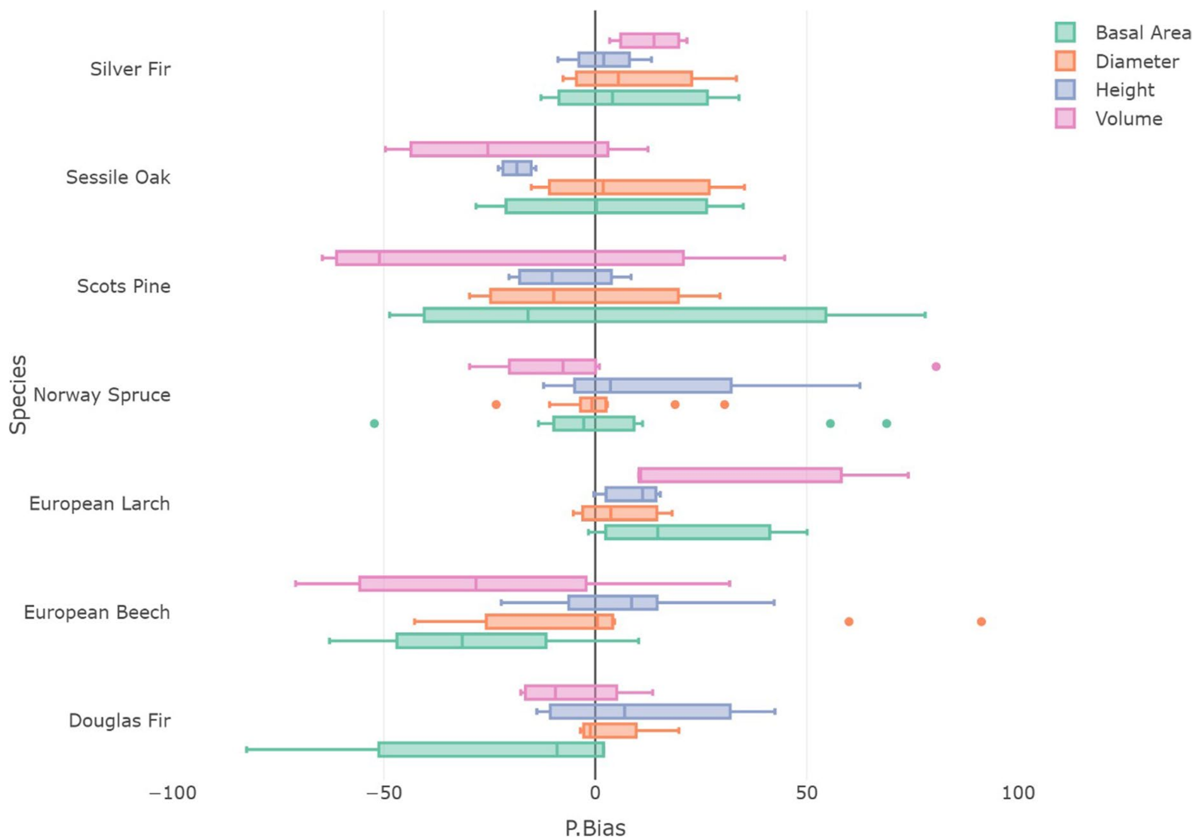

Fig. 18 The Pbias (*x*-axis (%)) values in the validation of the named tree species (*y*-axis) for basal area (green), diameter (orange), height (blue) and volume (pink)

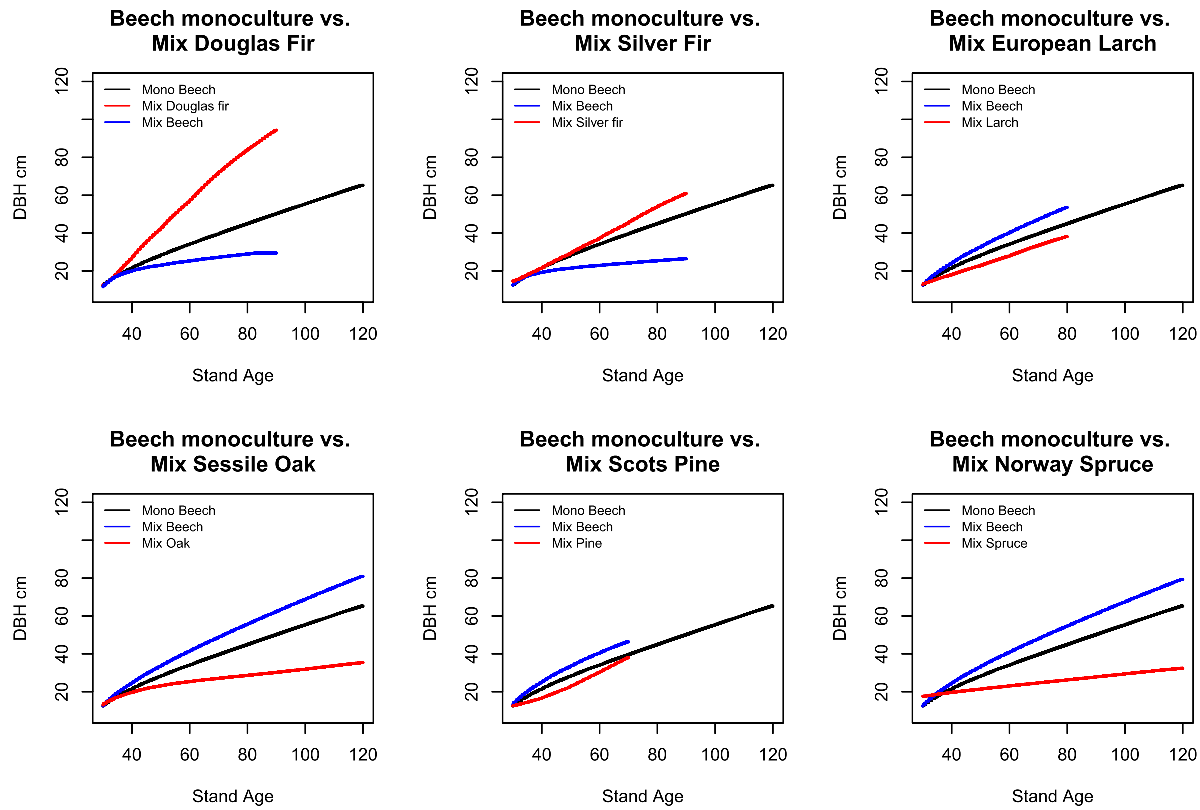

Fig. 19 "Business as usual" management. DBH (diameter at breast height, *y*-axis) vs. stand age (*x*-axis) simulations for beech, comparing the growth in monoculture (black) with its growth in mixture (blue) with another species (red)

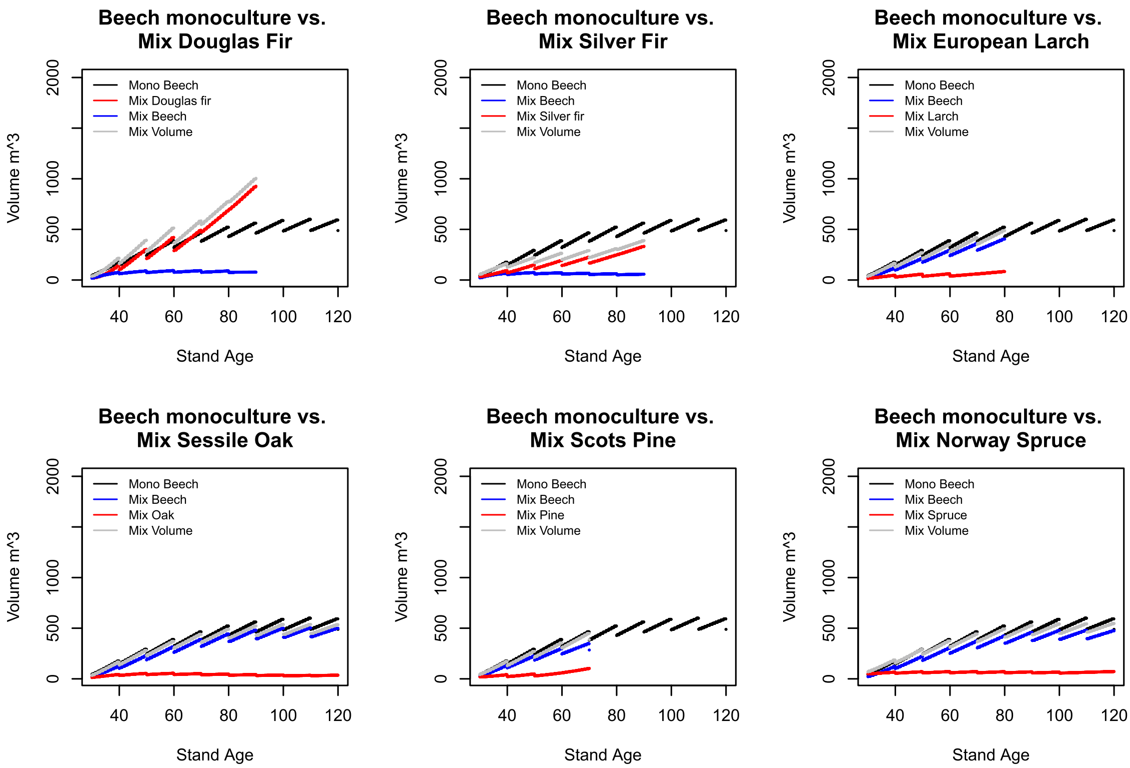

Fig. 20 "Business as usual" management. Volume (*y*-axis) vs. stand age (*x*-axis) simulations for beech, comparing the growth in monoculture (black) with its growth in mixture (blue) with another species (red)

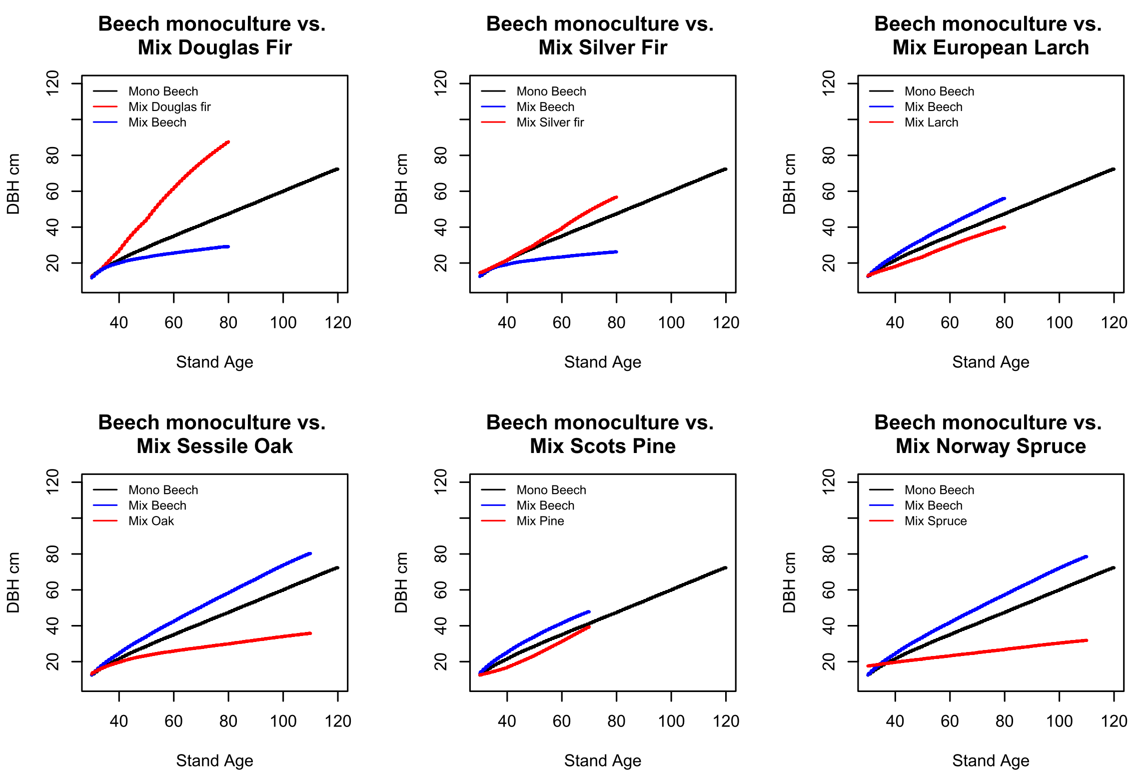

Fig. 21 High-intensity thinning. The above graphs show mean DBH (diameter at breast height, *y*-axis) vs. stand age (*x*-axis) simulations for beech, comparing the growth in monoculture (black) with its growth in mixture (blue) with another species (red)

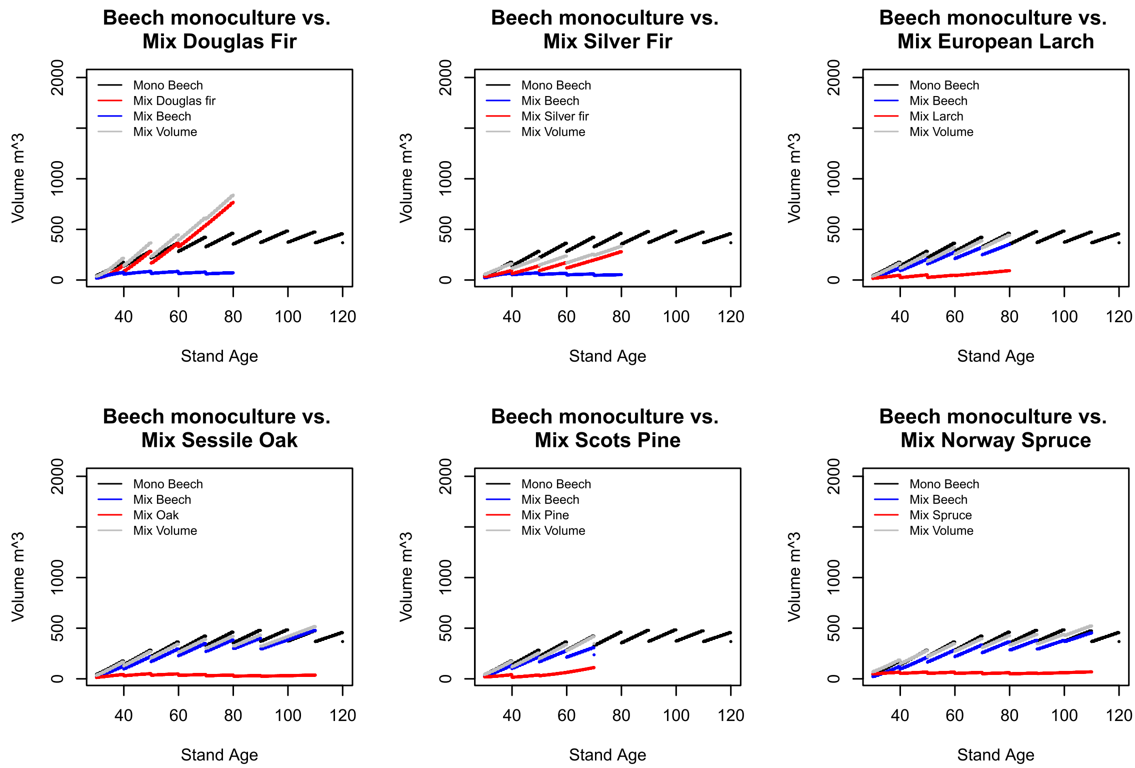

Fig. 22 High-intensity thinning. The above graphs show volume (*y*-axis) vs. stand age (*x*-axis) simulations for beech, comparing the growth in monoculture (black) with its growth in mixture (blue) with another species (red)

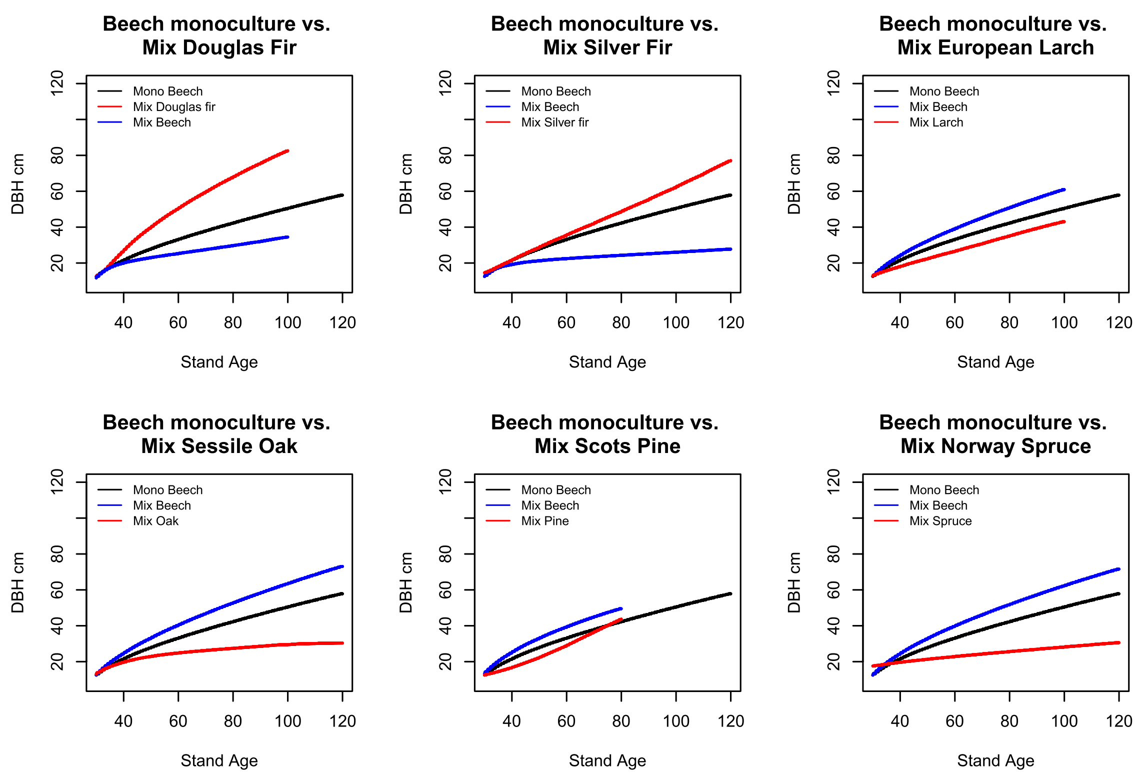

Fig. 23 Low-intensity thinning. The above graphs show mean DBH (diameter at breast height, *y*-axis) vs. stand age (*x*-axis) simulations for beech, comparing the growth in monoculture (black) with its growth in mixture (blue) with another species (red)

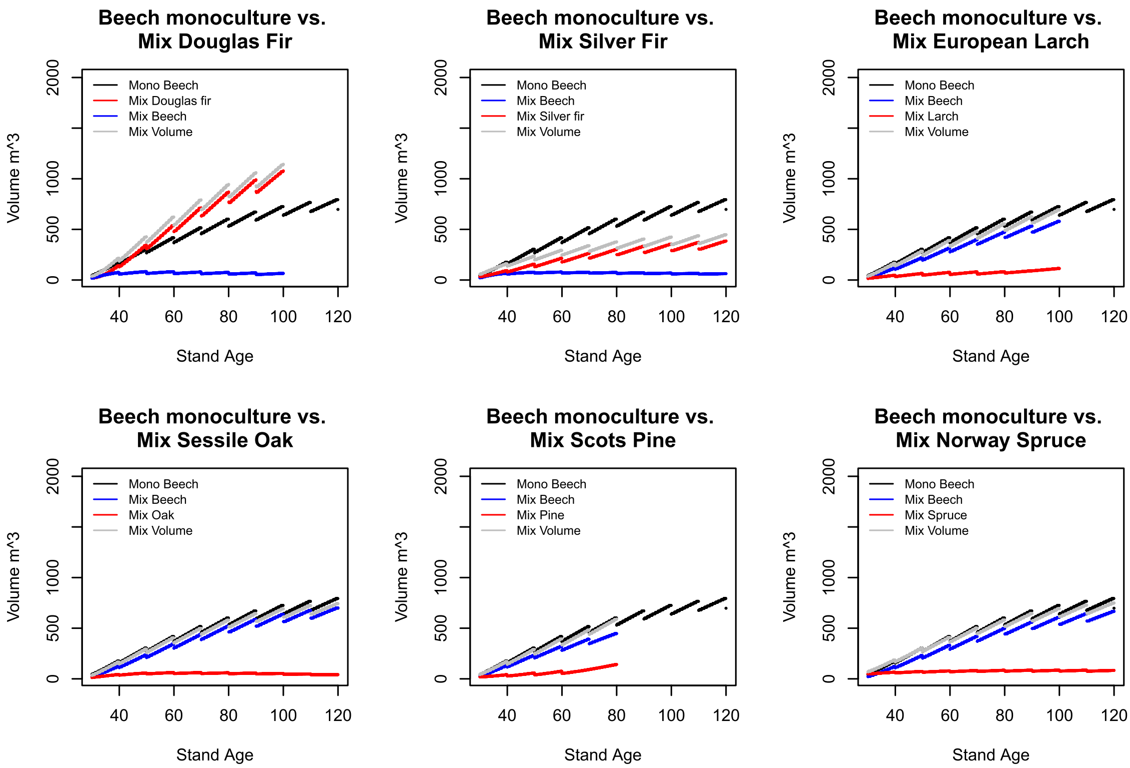

Fig. 24 Low-intensity thinning. The above graphs show volume (*y*-axis) vs. stand age (*x*-axis) simulations for beech, comparing the growth in monoculture (black) with its growth in mixture (blue) with another species (red)

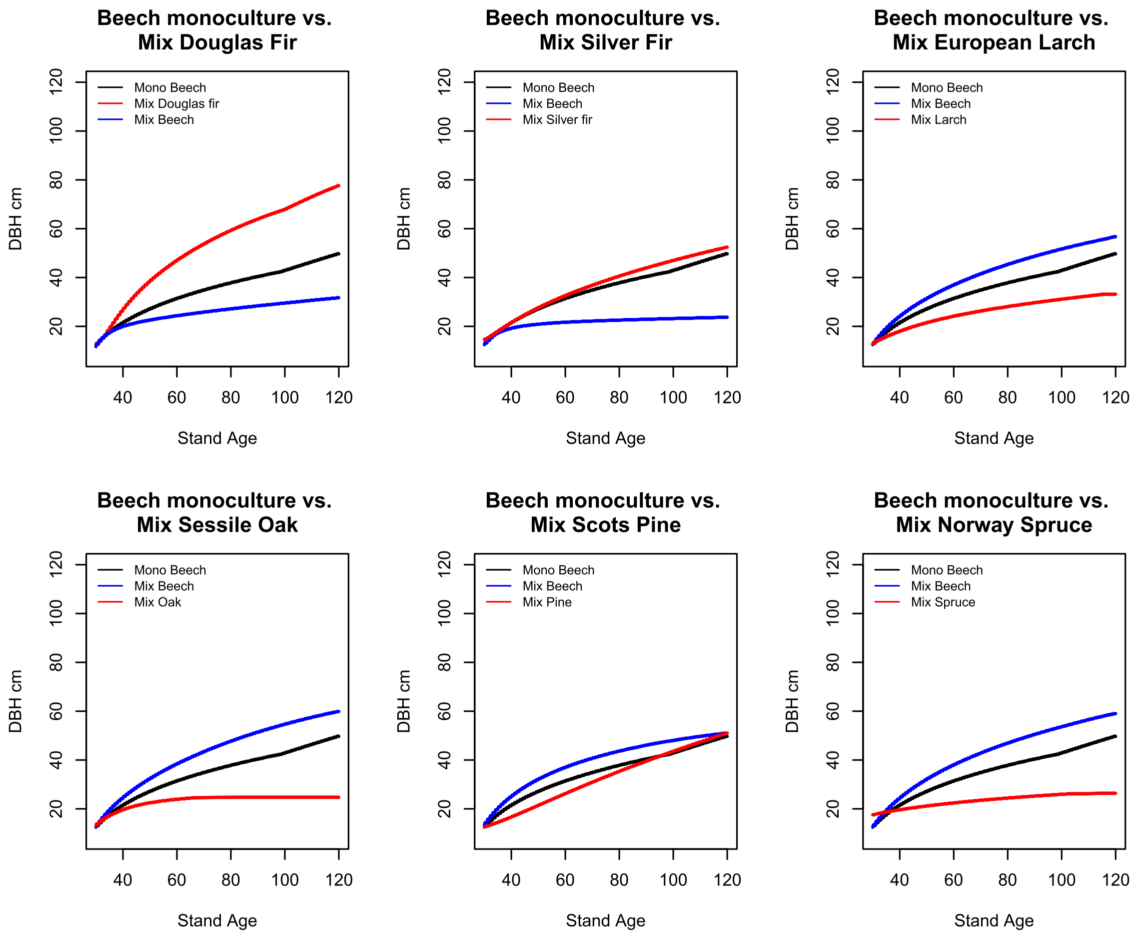

Fig. 25 No thinning. The above graphs show mean DBH (diameter at breast height, *y*-axis) vs. stand age (*x*-axis) simulations for beech, comparing the growth in monoculture (black) with its growth in mixture (blue) with another species (red)

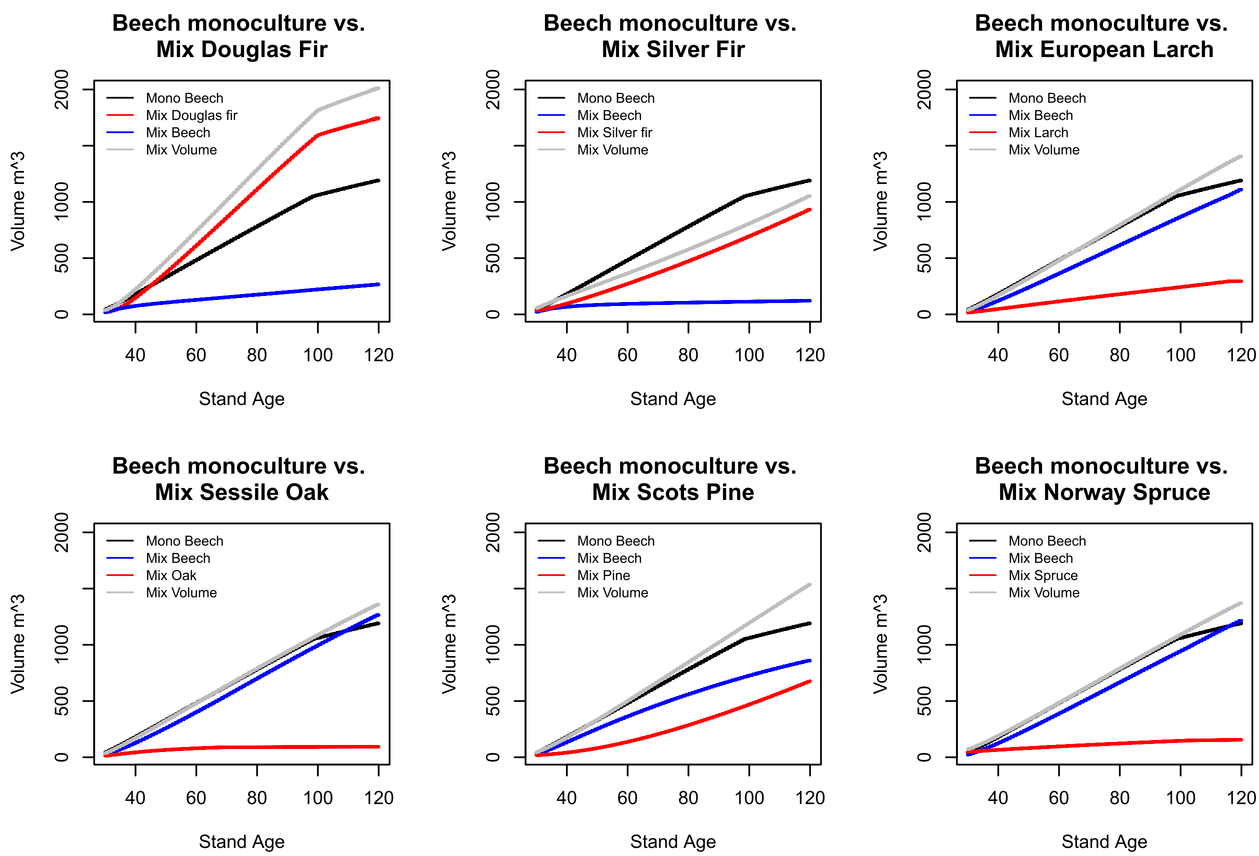

Fig. 26 No thinning. The above graphs show volume (*y*-axis) vs. stand age (*x*-axis) simulations for beech, comparing the growth in monoculture (black) with its growth in mixture (blue) with another species (red)

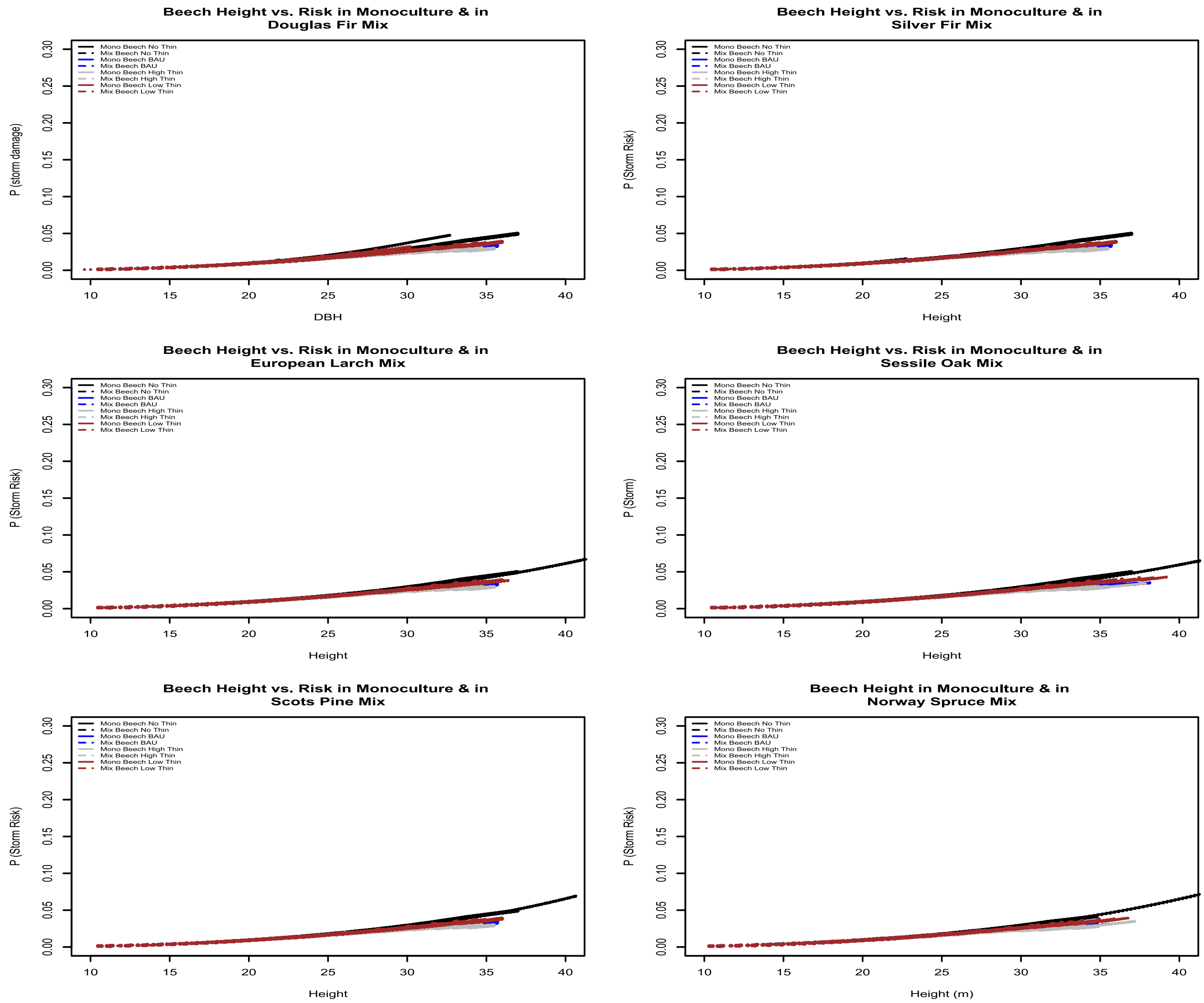

Fig. 27 Height vs. (P storm risk) plots of beech in monoculture and mixture with Douglas fir, silver fir, larch, oak and pine considering BAU, heavy thin, light thin and no-thin regimes

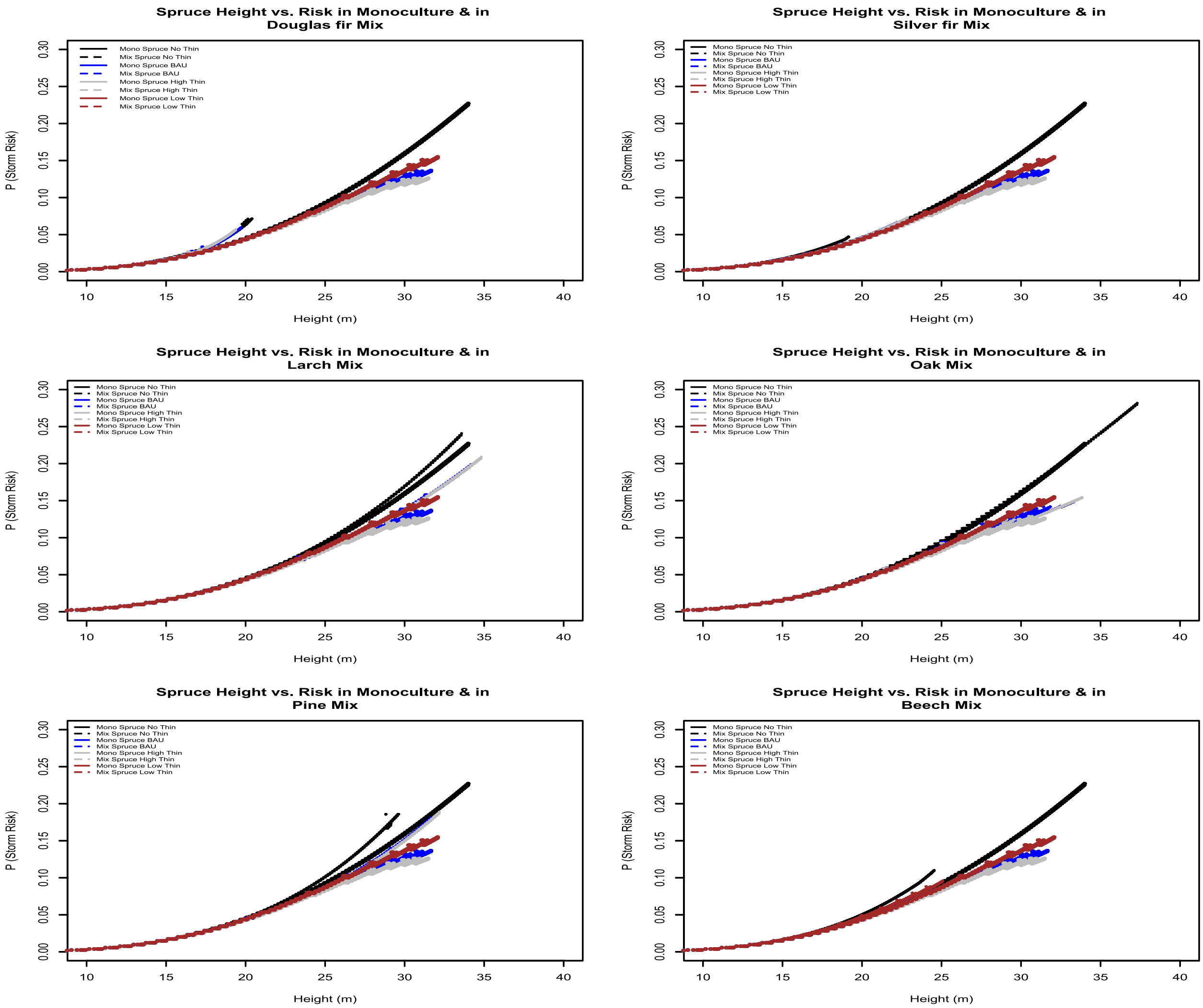

Fig. 28 Height vs. P (storm risk) plots of spruce in monoculture and mixture with Douglas fir, Silver fir, larch, oak and pine considering BAU, heavy thin, light thin and no-thin regimes

Appendix 4

Statistics

In Table 5 only pine mixed with larch was not different in its risk level to monoculture, as well as Silver fir mixtures with oak and pine. Spruce also did not see a significant difference when mixed with larch. All other mixture perutations showed significant difference.

Table 5 The below table shows the Mann–Whitney *U*- (where *W* is the test statistic) and *T*-test (where *t* is the test statistic and *df* is the degrees of freedom) results comparing damage probability (*P*-values) in all species for significant difference with the Mann–Whitney *U*- and *T*-tests (P & p)

	Mann–Whitney *U*-test		***T*-test**		
Species	***W***	***P***	***t***	***df***	***P***
Spruce/beech	1,383,578	2.2e-16	57.061	1546	2.2e-16
Spruce/Douglas fir	1,119,676	1.505e-07	2.3695	2690.7	0.01788
Spruce/silver fir	383,376	2.2e-16	− 40.404	1709.5	2.2e-16
Spruce/larch	283,920	2.2e-16	− 49.842	1537.4	2.2e-16
Spruce/oak	1,934,260	2.2e-16	67.653	1422.2	2.2e-16
Spruce/pine	1,808,500	2.2e-16	57.759	1456	2.2e-16
Beech/Douglas fir	1,444,634	2.2e-16	67.56	1621.7	2.2e-16
Beech/silver fir	1,298,474	2.2e-16	41.009	2343.8	2.2e-16
Beech/larch	1,167,974	2.2e-16	25.092	2422.7	2.2e-16
Beech/oak	187,296	2.2e-16	− 42.791	1166.7	2.2e-16
Beech/pine	775,032	0.6298	0.82968	1707.1	0.4068
Douglas fir/silver fir	294,120	2.2e-16	− 46.183	1877.3	2.2e-16
Douglas fir/larch	194,088	2.2e-16	− 58.593	1609.1	2.2e-16
Douglas fir/oak	26,568	2.2e-16	− 81.717	1425.3	2.2e-16
Douglas fir/pine	114,384	2.2e-16	− 68.988	1479.4	2.2e-16
Silver fir/larch	1,419,580	2.2e-16	22.001	2408.2	2.2e-16
Silver fir/oak	1,984,012	2.2e-16	77.51	1466.9	2.2e-16
Silver fir/pine	1,717,732	2.2e-16	45.673	1784.6	2.2e-16
Larch/oak	1,949,380	2.2e-16	79.835	1539.2	2.2e-16
Larch/pine	1,576,876	2.2e-16	30.603	2246.9	2.2e-16
Oak/pine	1,865,284	2.2e-16	76.516	1788.9	2.2e-16

Table 6 The below table shows the Mann–Whitney *U*- (where *W* is the test statistic) and *T*-test (where *t* is the test statistic and *df* is the degrees of freedom) results comparing storm damage probability (*P*-value) in soil fertility, soil water and soil type for a monoculture of Norway spruce

	Mann–Whitney *U*-test		***T*-test**		
Spruce	***W***	***p*-Value**	***t***	***df***	***p*-Value**
Fertility low/medium	999,672	0.7941	− 0.37742	2833.3	0.7059
Fertility low/high	996,048	0.6693	− 0.72723	2831.4	0.4671
Soil water low/medium	1,010,692	0.8069	0.010785	2834	0.9914
Soil water low/high	1,010,764	0.8043	0.021956	2834	0.9825
Soil clay/loam	1,010,476	0.8146	0.076402	2834	0.9391
Soil sandy/loam	1000,104	0.8094	− 0.02141	2834	0.9829
Soil sandy/clay	1000,104	0.8094	− 0.025089	2834	0.98

Appendix 5

Utilised R packages, functions & code overview

Model Parameterisation

Package: Bayesian Tools library(BayesianTools)

“Observed Data” <- “Reference Data” + rnorm(length(“Reference Data”), sd = “Parameter Standard Deviation”)

“Selected Parameters” <- c(i:j)

“Likelihood” <- function(“Parameters”, sum = TRUE) {

x <- “Initial Parameters”

“Predicted Data” <- “Model Output”

“Difference” <- c(“Predicted Data” – “Observed Data”)

“Likelihood Values” <- dnorm(“Difference”, sd = “Parameter Standard Deviation”, log = TRUE)

If (sum == FALSE) return(“Likelihood Values”)

Else return (sum(“Likelihood Values”)

}

“Prior Parameter Distributions” <- createUniformPrior(lower = “Lowest Known Parameter Value”, upper = “Highest Known Parameter Value”, best = “Initial Parameter Value”)

“Bayesian Setup” <- createBayesianSetup(“Likelihood”, prior = “Prior Parameter Distributions”, names = rownames = “Selected Parameters”)

“Settings” <- list(iterations = 1250, nrChains = 2)

“Posterior Parameter Distribution” <- runMCMC(bayesianSetup = “Bayesian Setup”, sampler = “DEzs”, settings = “Settings”)

Lothar Model Coupling # Stand data

“Dataframe”$BHD99 <- “Mean Stand Diameter”

“Dataframe”$BAGRG <- “Species”

“Dataframe”$H99 <- “Height”

“Dataframe”$HD99 <- “Height/Diameter Ratio”

“Dataframe”$sum_TOPEX1000_1_4 <- “Topex 1”

“Dataframe”$sum_TOPEX1000_14_27 <- “Topex 2”

“Dataframe”$sum_TOPEX1000_9_32 <- “Topex 3”

“Dataframe”$sum_TOPEX1000_22_19 <- “Topex 4”

“Dataframe”$RW <- “Longitude”

“Dataframe”$HW <- “Latitude”

Damage Prediction

“Prediction” <- predict(“Lothar Model”,newdata= ”Dataframe”)

“Prediction” <- 1 - (1/(1 + (exp(“Prediction”))))

#Fallen Stems and Lost Biomass

StemNoOld <- “Previous Stem Number”

StemNo <- “Current Stem Number” - (“Current Stem Number” * “Prediction”)

“Removed Stems” <- (StemNoOld - StemNo) / StemNoOld

“Foliage Biomass" <- “Foliage Biomass” * (1 - “Removed Stems” * “Biomass Lost Per Tree”)

“Root Biomass" <- “Root Biomass” * (1 - “Removed Stems” * “Biomass Lost Per Tree”)

“Stem Biomass" <- “Stem Biomass” * (1 - “Removed Stems” * “Biomass Lost Per Tree”)

“Average Stem Mass” <- “Stem Biomass” * 1000 / “Current Stem Number”

Net Present Value Calculation PriceStem <- “Stemwood Price” – “Harvesting Cost”

PriceInd <- “Industrialwood Price” – “Harvesting Cost”

PriceFuel <- “Fuelwood Price” – “Harvesting Cost

Stem <- “Proportion Sawlog” * PriceStem

Industry <- “Proportion Industrial Wood” * PriceInd

Fuel <- “Proportion Fuelwood” * PriceFuel

Net <- sum(Stem,Industry,Fuel)

“Revenue” <- (“Extracted Volume” - (“Extracted Volume” * “Unusable Proportion”)) * Net

“New Extracted Value” <- “Extracted Value” + (“Revenue” / ((1 + “Discount Rate”) ^ “Stand Age”))

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Authors’ contributions
All authors contributed to the conceptualization and methodology of the manuscript. RB performed all analyses and visualisation and wrote the main body of the text. RY provided general scientific supervision and review and editing of the manuscript. MH reviewed and edited the manuscript, as well as being responsible for project administration and project funding. The authors read and approved the final manuscript.

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Availability of data and materials
The datasets both analysed and generated for this manuscript are available from the corresponding author.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
All authors of this manuscript give their informed consent for its publication.

Competing interests
The authors declare that they have no competing interests.

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