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RESEARCH PAPER

Climate change and mixed forests: how do altered survival probabilities impact economically desirable species proportions of Norway spruce and European beech?

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Abstract

• ***Key message*** **Economic consequences of altered survival probabilities under climate change should be considered for regeneration planning in Southeast Germany. Findings suggest that species compositions of mixed stands obtained from continuous optimization may buffer but not completely mitigate economic consequences. Mixed stands of Norway spruce (*Picea abies* L. Karst.) and European beech (*Fagus sylvatica* L.) (considering biophysical interactions between tree species) were found to be more robust, against both perturbations in survival probabilities and economic input variables, compared to block mixtures (excluding biophysical interactions).**

• ***Context*** Climate change is expected to increase natural hazards in European forests. Uncertainty in expected tree mortality and resulting potential economic consequences complicate regeneration decisions.

• ***Aims*** This study aims to analyze the economic consequences of altered survival probabilities for mixing Norway spruce (*Picea abies* L. Karst.) and European beech (*Fagus sylvatica* L.) under different climate change scenarios. We investigate whether management strategies such as species selection and type of mixture (mixed stands vs. block mixture) could mitigate adverse financial effects of climate change.

• ***Methods*** The bio-economic modelling approach combines a parametric survival model with modern portfolio theory. We estimate the economically optimal species mix under climate change, accounting for the biophysical and economic effects of tree mixtures. The approach is demonstrated using an example from Southeast Germany.

• ***Results*** The optimal tree species mixtures under simulated climate change effects could buffer but not completely mitigate undesirable economic consequences. Even under optimally mixed forest stands, the risk-adjusted economic value decreased by 28%. Mixed stands economically outperform block mixtures for all climate scenarios.

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Contribution of the co-authors C.P., W.F., and T.K. conceived the original concept. S.B. carried out the statistical analysis of tree mortality data. S.F. and F.H. supported with preparation of climate and economic data. C.P. applied statistical analysis to study site and carried out economic analyses. C.P. wrote the manuscript. All others jointly discussed and revised the text of the manuscript.

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This article is part of the topical collection on Forest Adaptation and Restoration under Global Change

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• ***Conclusion*** Our results underline the importance of mixed stands to mitigate the economic consequences of climate change. Mechanistic bio-economic models help to understand consequences of uncertain input variables and to design purposeful adaptation strategies.

Keywords Survival analysis · Value at risk · Climate change · Species mixture · Forest restoration · Portfolio theory

1 Introduction

Tree species selection is a key strategic decision in forest management planning (Cubbage et al. 2007). Regeneration decisions generally depend on silvicultural considerations but will ultimately also be driven by economic considerations. Climate change is expected to change both, silvicultural suitability and expected returns, thus affecting regeneration decisions (Albert et al. 2017; Pukkala 2018; Schou et al. 2015; Yousefpour and Hanewinkel 2016). For Central Europe, models anticipate an increase in the frequency and severity of extreme weather events and resulting forest disturbances, such as wind throws, forest fires, or drought and related pathogen outbreaks (Gardiner et al. 2011; Jandl et al. 2015; Seidl et al. 2017). These developments may particularly affect the economically important Norway spruce (*Picea abies* (L.) Karst., further referred to as spruce), due to its higher susceptibility to hazards, such as drought (Albert et al. 2017), storm, and bark beetle outbreaks (Thiele et al. 2017) compared to broad-leaved species such as the European beech (*Fagus sylvatica* L., further referred to as beech) (Hanewinkel et al. 2011; Neuner et al. 2015). The planting of spruce into mixed stands has been suggested to increase stand resistance (Griess et al. 2012; Pretzsch et al. 2013). Therefore, the need for converting spruce-dominated forests towards less susceptible broad-leaved species is often accentuated (e.g., Teuffel et al. (2005)), while the reduction of spruce stands to extend the area of beech may lead to severe economic losses (Hanewinkel et al. 2010).

In order to quantify and compare the susceptibility of different species or forest types to natural hazards, empiric survival functions have increasingly been used (Griess et al. 2012; Neumann et al. 2017; Neuner et al. 2015; Nothdurft 2013; Staupendahl 2011; Thiele et al. 2017). In Southwest Germany, Neuner et al. (2015) demonstrated that tree survival of spruce under climate change may be increased through species admixture. Using a European-wide data set, and semiparametric survival functions, Neumann et al. (2017) showed the effects of climate variables and variability on disturbance patterns at the European level. While this study is valid for a large range of environmental conditions, it aggregates species to groups. Other, more species-specific studies have been limited to datasets in Southwest Germany (Griess et al. 2012; Neuner et al. 2015; Staupendahl and Zucchini 2011). The derived survival probabilities therefore only cover a limited range of climate conditions which restrict the application of future climate scenarios and potential effects on survival time of different species. The majority of climate change-related studies in forestry focus on silvicultural or yield science aspects, while economic consequences are assessed much less frequently (Thiele et al. 2017; Zubizarreta-Gerendiain et al. 2016). Neuner and Knoke (2017) are among the rare examples assessing the economic consequences of climate change for predefined mixed forest stand types. However, the survival functions used for this study only cover a limited environmental gradient.

Empiric survival functions of tree species have a particular appeal for integration into bio-economic decision models, to account for probability of stand failure (Burkhardt et al. 2014; Deegen and Matolepszy 2015; Staupendahl and Möhring 2011) and to estimate risk costs (Möllmann and Möhring 2017). These studies have mostly focused on adaptation strategies related to optimal rotation periods of single species. However, analyzing regeneration decisions in face of climate change requires the comparison of different species, as well as potential diversification strategies between them.

Portfolio theory following Markowitz (1952, 2010) has been used in forest economics to reflect consequences of tree species diversification, which may reduce risks (usually quantified as the standard deviation of returns) and aid species selection (Brunette et al. 2017; Dragicevic et al. 2016; Knoke et al. 2017). Empiric survival functions have so far occasionally been integrated in such bio-economic models (Griess and Knoke 2013; Neuner and Knoke 2017; Roessiger et al. 2013). Neuner and Knoke (2017) showed that climate change effects were economically less important in changing risks and returns compared to diversification and management strategies such as planting and pruning. This study could, however, only use a small set of predefined tree species mixtures. Investigating desirable species portfolios for different climate scenarios would need to go beyond predefined species mixtures, requiring information on survival probabilities for continuously changing tree species proportions under different climate conditions.

The use of empirical survival probabilities in bio-economic models has great relevance for risk-averse forest owners (Griess and Knoke 2013; Roessiger et al. 2013). Although forest owners consider risks in their decisions (Blennow and Sallnäs 2002; Seidl et al. 2016), the adaptation threshold for changing forest management strategies is still high (Eriksson 2014). This may be attributed to the uncertainty in expected consequences of climate change, which may delay adaptation strategies in regeneration decisions (Schou et al. 2015). A better understanding of the economic effects of altered survival probabilities has the potential of aiding regeneration decisions under climate change, thus avoiding adverse economic consequences for forest owners. Our objective was therefore to analyze the impact of altered survival probabilities on economically driven regeneration decisions, while accounting for economic and biophysical effects of tree species diversification.

In contrast to approaches used in the real options' theory (Schou et al. 2015; Yemshanov et al. 2015) and Bayesian updating (Yousefpour et al. 2014), which build on adaptation through updating information, here, we refer to adaptation in terms of changing tree species composition at the beginning of a forest's production. Once established, species mixtures may not immediately be changed for long periods without the need of carrying out harvesting operations in premature stands. Thus, the regeneration decision, investigated in this study, is a static decision at a defined point in time and based on information currently available. To illustrate the bio-economic approach, we used an example study site from Southeast Germany, focusing on spruce and beech. With this example, we refer to the challenge of supporting regeneration decisions following large-scale wind throw. This question is of high relevance for forest owners and political decision-makers in order to reduce the economic consequences of climate change and to design supportive policies.

For our study site, we investigate the overarching research hypothesis: *Under the adverse effects of climate change on tree survival, mixed forests dominated by beech are economically superior to spruce-dominated forests.* In this context, we also hypothesize that *the type of mixture in which these forests are established, in terms of mixed stands (allowing for interactions between tree species) or block mixture (mixed at forest level, excluding interactions between tree species), does not influence the optimal species composition.*

In order to contribute to this research hypothesis, we combined two key model components, which can be broadly applied to other sites, with a focus on Central Europe: First, we developed a model for analyzing climate effects on tree survival probabilities in Germany. The tree species-specific empiric survival model uses a European dataset and allows for model parametrization with a wide set of climate conditions, thus mimicking potential future climate conditions. This approach goes beyond existing survival modelling so far used in bio-economic models (e.g., Möllmann and Möhring 2017; Neuner and Knoke 2017). This is not only in terms of the extended data base. We also incorporated substantial methodological improvements in variable selection and model fitting using left-truncated and right-censored data—a situation often found in forest inventory. Second, we integrated this novel empiric model into a bio-economic simulation and optimization model, which builds on Monte Carlo Simulation and Portfolio Theory (Griess and Knoke 2013; Neuner and Knoke 2017). Our new and extended bio-economic modelling approach allows us to compare a principally unlimited set of different species proportions (as continuous decision variables) between two different diversification approaches: one excluding and one including biophysical interactions between tree species. The effects of mixture refer to tree survival based on our empiric model. We also account for potential effects on growth and timber quality of stands, while these are not the focus of our study. In summary, we can therefore investigate the influence of future climate scenarios to (1) the economically ideal species proportions and (2) the optimal type of mixture. This simulation-optimization approach also allowed us to (3) investigate the sensitivity of tree species selection on altered survival probabilities compared to other model assumptions, such as planting costs, discount rate, risk attitude, and coefficient of correlation between returns of the two species.

2 Materials and methods

2.1 Deriving survival probabilities under current and future climate

2.1.1 Modelling tree survival

In this study, we build on the parametric survival model for assessing tree survival developed and applied by Staupendahl (2011), Staupendahl and Zucchini (2011), Griess et al. (2012), and Neuner et al. (2015) for Germany. Survival time is assumed to follow the Weibull distribution. The parameters of the distribution and the impact of covariates on survival time are estimated by an Accelerated Failure Time (AFT) model. The probability of survival S at a certain time t, reflecting tree age, can be described by:

$$S(t) = \exp\left[-\left(\frac{t}{\beta}\right)^{\alpha}\right] \text{ with } t \geq 0 \tag{1}$$

with α being the shape and β being the scale parameter. The shape parameter α represents the development of the hazards over time. According to Staupendahl (2011), values of one express a constant risk over time. Smaller or larger values express a decreasing or increasing hazard rate over time, respectively. Covariates are assumed to increase or decrease survival time and act on the scale parameter β. A detailed description accompanies the results in Table 1 (Appendix). Staupendahl and Möhring (2011) have outlined the advantages of this approach for supporting decision-making in forest management. First, age-dependent survival probability can be directly transferred into the conditional dropout probability of a stand, which has survived until a certain age class. This information is needed for appropriate discounting in discrete time. Second, the function is described by only two parameters compared to, for example, polynomial equations as used by Knoke and Wurm (2006) and Knoke and Seifert (2008).

2.1.2 Data used for parametrization and variable selection

Compared to earlier studies (Griess et al. 2012; Neuner et al. 2015), we use a further extended pan-European dataset on crown condition from Level I (systematic 16 × 16 km grid) and Level II (intensive monitoring sites) plots provided by ICP Forests[1] (International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests) (ICP Forests 2018). In general, the crown condition of sample trees is recorded annually. In order to identify mortality events, the cause of removal of a tree is an essential information (Eichhorn et al. 2016). Level I data provide this information since 2011. Details on the survey design and methods can be found in UNECE ICP Forests (2016). The dataset was complemented by data from the German Crown Condition Survey provided by the Thünen Institute of Forest Ecosystems (see footnote[1] for data availability and Wellbrock et al. 2018 for description of the dataset), which is available at a denser grid and provides a longer time series as well as more exact information on tree age (see Electronic Supplementary Material (ESM) Tables S1 and S2 and Fig. S1). The dataset is available from the Thünen Institute upon request. Using the pan-European dataset, the model can be fitted based on a wider range of temperature and precipitation factors, which improves the prediction of potential effects of future climate change on tree species survival and its applicability as a "space for time" approach (see also Neumann et al. (2017)). While earlier studies have mostly focused on spruce, here, we also incorporate the effect of climate variables and tree mixture on the survival time of beech.

The set of potential explanatory variables consisted of mixture proportions of the respective species as well as different climate variables taken from the BioClim variables available from the WorldClim database. The freely available dataset (see WorldClim 2018b) provides interpolations of observed climate data, which is representative for the time period 1960–1990 (see Hijmans et al. 2005 for details). We used the highest available resolution of 30 arc-seconds. The available bioclimatic (BioClim) variables were grouped into variables characterizing mean annual temperature or summer temperature, winter temperature, and precipitation (ESM Table S3). In order to prevent high collinearity between explanatory variables (Dormann et al. 2013), only one variable could be selected from each group. The variables could enter the model either as linear effect or as spline, thus accounting for potentially non-linear effects. The models' predictive performance was evaluated with 10-fold cross-validation (relation of data splitting train data: test data = 9: 1). The Brier score (Gerds and Schumacher 2006) was used as a determinant of prediction accuracy and model improvement. Left truncation of data was accounted for, as observation of a tree does not start at germination. In addition, we used a start age of 20 years, since very young trees are underrepresented in the data; this could lead to unrealistic survival probabilities at these ages (Moore 2016). We thus exclude risks in young stands and assume that through appropriate establishment and management techniques, stand establishment is successful.

To the best of our knowledge, this is the first study investigating the effects of tree mixture on both tree species and for a continuous set of mixtures. All analyses were carried out using the R programming language and environment (R Core Team 2017) using the packages "survival" (Therneau and Grambsch 2001) and "eha" (Broström 2015).

2.2 Economic analysis

2.2.1 Definition of alternatives

The aim of our study was not only to compare two mutually exclusive alternatives, made up by either planting tree species A or B (in our case spruce or beech), but also to allow for a mix of species. Consequently, the percentages forming the actual tree species mixture have not been predefined. We contrasted the following two types of mixtures: (1) *block mixture:* Following Knoke and Seifert (2008), we assumed that tree species were planted in large blocks, which may be mixed at the enterprise level. Biophysical interactions between tree species were excluded. Growth and survival thus correspond to that of monospecies stands. (2) *Mixed stands:* Here, we assumed a mixture of small species cohorts (groups of ~ 1000 m^2) to be within the stand, following Knoke and Seifert (2008). Biophysical interactions between tree species in mixed stands were assumed to affect stand resistance in accordance with results of our survival model (results will be described in "Plausible ranges of survival probabilities"). Mixing the two species within a stand was furthermore assumed to affect volume growth and wood quality. Here, we used the assumptions derived from Knoke and Seifert (2008) as applied in Griess and Knoke (2013) and Neuner and Knoke (2017). While spruce benefits from admixture with beech, beech suffers from a slight decrease in quality (ESM Table S8). Taken together, the effects on volume growth and wood quality lead to an increase in (nominal) returns from wood harvesting by up to + 15% for spruce and a decrease for beech of up to − 10% (ESM Table S8).

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[1] Data is provided upon request via the Programme Co-ordinating Centre at the Thünen Institute of Forest Ecosystems in Eberswalde, Germany (see icp-forests.net/data-requests).

2.2.2 Modern portfolio theory for deriving economically optimal species compositions

Here, we built on the general mean-variance analysis, which compares not only expected returns but also risks of different investments, based on statistical considerations (Markowitz 1952; Markowitz and Blay 2014). Given that expected returns of assets (e.g., investment in different tree species) are not perfectly correlated, diversification will reduce the standard deviation of the portfolio's return. Diversification can be achieved by assigning different weights to individual asset returns. In the context of silvicultural and land-use decisions, this translates into an allocation of forest area (or shares of area of the forest enterprise) for different tree species (Brunette et al. 2017; Dragicevic et al. 2016; Macmillan 1992). Following portfolio theory, the decision-maker would exclusively select "efficient" tree species portfolios. These are defined as combinations of assets which give the highest return for a given level of risk. The accepted level of risk, in terms of standard deviation of return, has to be estimated and depends on the individual risk attitude. Among a range of options in portfolio selection (Elton et al. 2014), the Value at Risk (VaR) (Jorion 2009) has frequently been used in forest management decisions, to illustrate risk aversion of forest (Couture et al. 2016; Hahn et al. 2014; Härtl et al. 2016) and land owners (Estrada et al. 2011; Wan et al. 2015) and to select a specific "optimal forest composition." Following the original ideas of Kataoka (1963), the VaR is a downside risk measure, which calculates the expected portfolio return at a specified quantile (we used 5%) at the undesirable (here left) tail of the return distribution. It can be interpreted as the return, which is exceeded with a probability of 95%. We used the maximization of this criterion to identify economically optimal tree species compositions for block mixtures and mixed stands under current and expected future climate conditions.

Following the notation by Elton et al. (2014), the $\mathrm{VaR_p}$ is estimated as

$$\mathrm{VaR_p} = E\left(\mathrm{R_p}\right) - z_{\varphi} \times s_{\mathrm{p}} \tag{2}$$

subject to $E(R_{\mathrm{p}}) \sim N(\mu;\, \sigma^2)$

With $E(R_{\mathrm{p}})$ being the expected portfolio return, z_{φ} is a constant derived from the Gaussian normal distribution ($N(\mu;\, \sigma^2)$), depending on the quantile of the distribution to be considered. We used z_{φ} of 1.65 for a 5% shortfall probability φ (corresponding to the 95% quantile). For block mixtures, $E(R_{\mathrm{p}})$ can be calculated as the weighted mean of individual returns of the assets i and j (in our example returns of tree species A and B) and their standard deviation s_{p} is estimated by:

$$\begin{aligned} s_{\mathrm{P}} &= \sqrt{\sum_i \sum_j w_i w_j \mathrm{cov}_{ij}} \\ &= \sqrt{w_{\mathrm{A}}^2\, s_{\mathrm{A}}^2 + w_{\mathrm{B}}^2\, s_{\mathrm{B}}^2 + 2\, w_{\mathrm{A}} w_{\mathrm{B}} \mathrm{cov}_{\mathrm{A,B}}} \end{aligned} \tag{3}$$

subject to

$$\begin{aligned} &w_{\mathrm{A}} + w_{\mathrm{B}} = 1; w_{\mathrm{A}}, w_{\mathrm{B}} \geq 0 \\ &\mathrm{cov}_{\mathrm{A,B}} = k_{\mathrm{A,B}} s_{\mathrm{A}} s_{\mathrm{B}} \end{aligned}$$

with w_{A} and w_{B} being the weight (i.e., area) assigned to tree species and $k_{\mathrm{A,B}}$ being the coefficients of correlation between returns of the two tree species. For mixed stands, returns and risks were directly simulated (see below) for a range of mixtures between spruce proportions (in terms of stand area) of 10 to 90% in 10 percentage point increments.

2.2.3 Deriving return distributions

Frequency distributions of return ($E(R)$) were estimated by means of Monte Carlo simulation (MCS) and 10,000 iterations, incorporating tree and mixture specific survival probabilities and timber price fluctuations. This approach follows the study by Neuner and Knoke (2017). Production period was divided into age classes with a width of 10 years. Simulation began at age 0, assuming bare land, reflecting the assumed situation at the example site and following the basic assumptions of Faustmann for the Land Expectation Value (LEV) (Faustmann 1849). The respective survival probability derived from the statistical model was translated into conditional dropout probability (according to Staupendahl and Möhring (2011)), which was then implemented into the simulation through a binomial distribution of failure or no failure at the end of each age class (Griess and Knoke 2013). In the case of undamaged stands, returns from regular thinning and regular harvest (at end of rotation period T) were simulated for each point in time t. In case of a simulated hazard, return from timber sales was reduced by 50% according to Dieter et al. (2001). Immediate replanting of stands was simulated and age was set to 0, which meant that the simulation run stopped and a new simulation run (i.e., rotation) started. Wood price fluctuations were integrated via bootstrapping using historical timber prices (described in more detail below).

In our analysis, expected portfolio return $E(R_{\mathrm{p}})$ is represented by the LEV, which corresponds to a net present value (NPV) accumulated over an infinite time horizon. Following Griess and Knoke (2013) and Clasen et al. (2011), the LEV of the simulation run i (LEV_i) was calculated as the sum of the NPV of the simulated individual rotation (NPV_i) and the appropriately discounted mean LEV of the future rotations ($\overline{\mathrm{LEV}}$) (Eq. 4).

$$\mathrm{LEV}_i \ = \mathrm{NPV}_i \ \overline{+\mathrm{LEV}}\cdot \mathrm{q}^{-T_i} \tag{4}$$

with

$$\overline{\mathrm{LEV}} = \overline{\mathrm{NPV}}\cdot \frac{q^{\overline{T}}}{q^{\overline{T}}-1}$$
$$q = (1+r); \overset{\hat{E}}{r}0$$

NPV$_i$ is calculated as the sum of the discounted net cash flows in each year over the simulated rotation length T_i. T_i corresponds to the planned rotation time T or the time when the simulation is stopped, due to failure. To account for the fact that replanting of the subsequent forest generation is carried out earlier in case of failure, an average expected LEV of future generations (i.e., $\overline{\mathrm{LEV}}$) was calculated. For deriving $\overline{\mathrm{LEV}}$, the average $\overline{\mathrm{NPV}}$ for 10,000 simulated rotations and the corresponding average rotation lengths $\overline{T}$ until hazard occurred was estimated. $\overline{\mathrm{LEV}}$ was added to NPV$_i$ and discounted according to the elapsed time period when simulation stopped, using discount rate r. In accordance with Deegen and Matolepszy (2015), we used a constant discount rate of 1.5% for the baseline assumption. To allow for a simpler interpretation, results are presented as yearly land rent (annuity) estimated through multiplying LEV$_i$ by the discount rate r.

2.3 Example study site and data

We selected the district of Freyung in the Bavarian forest, located in the Southeast of Germany as an example site for our analysis. On August 18 of 2017, the region experienced an extreme storm event (“Kolle”). Local authorities estimated an amount of 2.3 Mio m^3 of storm-damaged timber and offered 60 Mio € of financial help to affected forest owners (BayStMELF 2017). The crucial question arising in such situations pertains to which tree species to incentivize and recommend to affected forest owners. The application example represents a typical situation of forest restoration in Central Europe, whereas developed methods are transferable to other regions.

2.3.1 Climate data

We used our statistical survival model to simulate economic consequences and silvicultural adaptation strategies for a range of climate scenarios. We used climate data from the freely accessible WorldClim database (version 1.4). Today’s climate is characterized as average of the time period 1960–1990 (Hijmans et al. 2005; WorldClim 2018b). Future climate scenarios are based on the Max-Planck-Institute Earth System Model at base resolution (MPI-ESM-LR). For this climate model, the Representative Concentration Pathway (RCP) scenarios 2.6, 4.5, and 8.5 are available for the period 2061–2080 (ESM Table S4) (WorldClim 2018a).The climate projections are downscaled and bias corrected using WorldClim 1.4 as baseline “current” climate and also provided in the WorldClim database. We used the highest available spatial resolution of 30 s (~ 1 km).

2.3.2 Forest data

We used growth simulation and cost estimates for spruce and beech available from Clasen et al. (2011) in the Bavarian Forest region (ESM Tables S5 and S6). Tree growth was originally simulated by Clasen et al. (2011) using the single-tree-based stand simulator SILVA (version 2.2) (Pretzsch et al. 2002) (see ESM Table S5). Thinning was carried out at a fixed amount in each decade according to results from the growth simulator (Table S5). Hence, in accordance with the survival model, when referring to “mortality,” we only refer to those trees, which would not have regularly been harvested during thinning or at the end of the planned rotation period. We used updated planting costs by data from Roessiger et al. (2013) and Messerer et al. (2017) reporting moderate values of 2000 € ha^{-1} for spruce and 3000 € ha^{-1} for beech. The use of potential natural regeneration in future generations, when rotation period reaches adequate tree age, was taken into account by using decreasing planting costs for the following rotation cycle (ESM Table S7). Planned rotation length was set at 120 years for beech and 90 for spruce according to the optimal rotation age of a risk-free consideration of annualized LEV at a constant discount rate of 1.5% (ESM Fig. S2). Resulting nominal net returns (excluding price fluctuations) for the planned rotation and in case of stand failure are summarized in the ESM Table S6. Timber price fluctuations were updated using the price quotients published by Messerer et al. (2017) for the period of 1975 to 2014.

2.4 Sensitivity analysis

While climate change is hypothesized to affect economic tree species selection, we also aimed to compare the magnitude of change in the optimized species composition to other important economic drivers. These include investment costs, Pearson correlation between returns, discount rate, and the assumed attitude towards risks. We carried out a sensitivity analysis by varying the input variables by up to ± 75% compared to the “baseline assumption,” which refers to current (constant) climate conditions and assumptions described above. Please note that for alterations in the correlation coefficient, we tested absolute values of $k_{\mathrm{A,B}}$ between ± 0.75 rather than relative changes.

3 Results

3.1 Plausible ranges of survival probabilities

Based on the European dataset, survival probabilities of spruce were best described by the climate variables "sum of precipitation in the warmest quarter" and "mean temperature of warmest quarter," as well as the share of spruce in the stand (see Table 1 for coefficients). For beech, the explanatory variables "maximum temperature of the warmest month" and the "minimum temperature of the coldest month" were chosen according to the selection procedure. Since the effect of tree mixtures on tree survival is one of the key questions of our research, we also included the share of beech in the stand as an explanatory variable. The inclusion of this variable only marginally increased the Brier score by a value of 0.001.

Both species showed a positive effect of admixture on tree survival (Table 1). The shape parameter α of the Weibull distribution was similar for both tree species with 1.27 for beech and 1.30 for spruce (ESM Table S9), both indicating an increase in hazard rate with age. Being rather close to 1.0, the shape parameter reflects that hazard increases on a diminishing scale. Given the climate variables of our study site, we found that the survival probability of beech remained considerably higher than that of spruce. The probability of a tree in pure stands to still being alive at age 100 ($S(100)$) was 0.49 for spruce and 0.80 for beech, under a current climate at the study site (see lowest lines in Fig. 1 and ESM Table S9).

Climate change affected both species at a similar magnitude. Yet, due to the higher survival of beech under current climate, its absolute survival rates still remained at a much higher level compared to spruce. For example, under the most pessimistic climate change scenario (RCP 8.5), $S(100)$ dropped down to 0.37 and 0.69 for pure spruce and beech stands, respectively (Fig. 1 and ESM Table S9). Given the stabilizing effect of species mixtures, our model suggests that the survival probability of spruce trees could still be maintained at today's level when admixing pure spruce stands with 40% beech. The level of uncertainty in predicting the effect of climate variables on tree survival was much higher for beech than for spruce, particularly for temperature-related variables (Table 1). This might be because events (i.e., occurrence of death) in the data set of beech are not so closely related to temperature (e.g., storm), whereas most dominant disturbance agents of spruce such as bark beetle show a stronger relation with temperature (Seidl et al. 2014).

3.2 Effect of climate change on economically optimal block mixtures

For our example site and applying the average expected survival rates under today's conditions, we obtained expected annuities of 117 (± 44) € ha^{-1} year^{-1} for pure spruce and 39 (± 22) € ha^{-1} year^{-1} for pure beech stands, respectively. Despite its higher survival probabilities, beech had a much lower return and higher coefficient of variation (67%) compared to spruce (38%). This may be attributed to the much higher growth volume of spruce (ESM Table S8), its shorter rotation cycle, and lower planting costs compared to beech. Consequently, pure spruce stands would also give a much higher VaR (43 € ha^{-1} year^{-1}) compared to pure beech stands (2 € ha^{-1} year^{-1}) (see gray solid line in Fig. 2). Even when allowing the model to mix pure spruce and beech stands, it would still choose to dedicate the entire regeneration area to pure spruce stands. Hence, economic benefits of diversification from selling to various timber markets could not compensate for the high VaR of pure spruce stands (see gray circle in Fig. 2 and ESM Table S10).

The consideration of the effect of climate change through altered survival probabilities only slightly reduced the economically optimal spruce proportion for a risk-averse forest owner (see black solid line and black circle in Fig. 2 for RCP 8.5 scenario). For the moderate RCP 2.5 scenario, the highest VaR was achieved by planting pure spruce stands, while excluding biophysical interactions. Only under the RCP 4.5 scenario, would the economically optimal spruce proportion in a block mixture be reduced to 95% and further down to 81% under the RCP 8.5 scenario (Figs. 2 and 3a). The respective maximum VaR, represented here by the assumed objective function of the forest owner, was reduced by 18, 27, and 46% for the RCP scenarios 2.5, 4.5, and 8.5, respectively (circles in Fig. 3b). Expected portfolio return of the optimized species portfolios would decrease by up to 26% (circles in Fig. 3c).

This result reveals that even if the forest owner followed economically optimal adaptation measures to climate change by adjusting species composition, he would most likely still experience financial losses. We also found that for a block mixture design, the economically optimized regeneration planning would still be clearly dominated by spruce. This finding holds even under the most extreme climate scenario.

3.3 Stabilizing effect of mixed tree stands

The increased survival probabilities found for both species when grown in mixed stands (cf. Fig. 1) resulted in a considerably higher VaR compared to block-wise mixtures (dashed lines in Fig. 2 and triangles in Fig. 3b). Under a constant climate, the VaR of the economically optimal species proportion in the mixed stand design was 19% higher compared to the highest VaR attainable in block mixture (compare dashed gray lines to solid gray lines in Fig. 2). This advantage even increased to up to 57% under the climate change scenarios (Figs. 2 and 3b).

However, despite the stabilizing effect of horizontal heterogeneity, climate change would still affect the forest owner. For

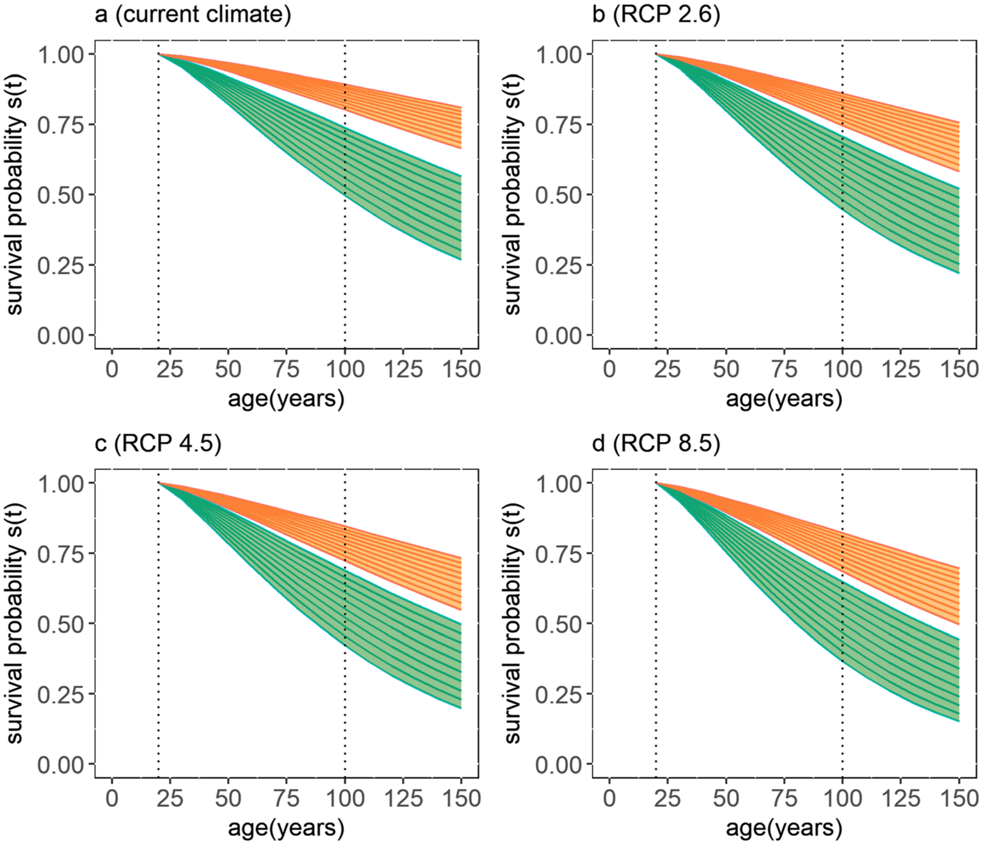

Fig. 1 Survival probabilities of beech (orange) and spruce (green) for the study site under current (**a**) and potential future climate, reflected by RCP 2.6 (**b**), RPC 4.5 (**c**), and RCP 8.5 (**d**) climate scenarios. Lines and shaded areas represent different species compositions in mixed stands, ranging from pure stands (lowest lines) to 10% of the respective species (upper lines) (see also ESM Table S9). Dashed vertical lines display the starting age of our model of 20 years (left line) and the reference age of 100 years, to which we refer as *s*(100) (see also ESM Table S9)

example, here the assumed objective function of the risk-averse forest owner (VaR) would still be reduced by up to 28% (for RCP 8.5) (Fig. 3b). Yet, compared to block mixtures and pure stands, economic consequences could be buffered considerably. The difference in absolute portfolio return between the optimized block mixture and mixed stands also declined with increasing severity of the climate scenario (Fig. 3c and ESM Table S11 for data on all mixtures).

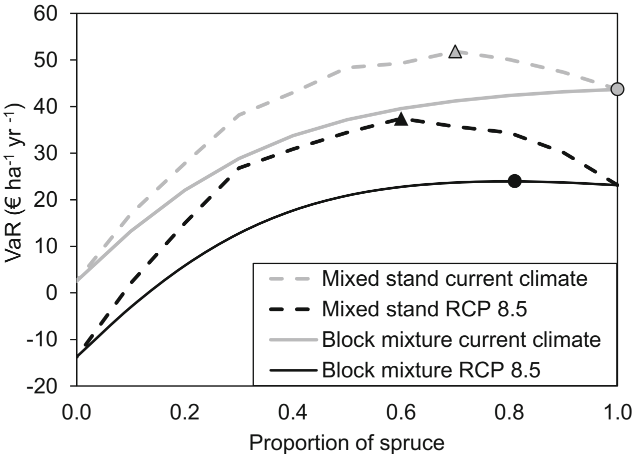

Fig. 2 Value at risk (VaR) under constant (current) climate (gray) and the most severe climate change scenario (RCP 8.5, black) for pure stands of spruce (proportion of spruce = 1) and beech (proportion of spruce = 0), compared to mixtures in blocks (solid lines) and mixed stands (dashed lines). Optimal stand compositions are given by triangles for mixed stands and circles for block mixtures and refer to respective symbols in Fig. 3 (see also ESM Tables S10 and S11)

The economically optimal spruce proportion in mixed tree stands was with 60–70% generally lower compared to the ideal block mixtures (Fig. 2). The effect was consistent for all climate scenarios studied (Fig. 3a). In our model, individual returns of spruce increase with an increasing admixture of beech. This is due to the higher stand resistance associated with lower hazard-induced losses and the shortening of rotation periods. The same effect was found for beech but was less pronounced, due to the various effects of admixture on tree growth and wood quality (see Knoke and Seifert (2008)). Consequently, given the overall higher return of spruce, this species still dominates the species portfolio of mixed stands. Even those mixed stands with spruce proportions larger than that of the optimal portfolio still outcompeted block mixtures. For instance, the VaR of a mixed stand with a share of 90% spruce, under the RCP 8.5 scenario, still gave a 26% higher VaR compared to the optimal block mixture with a lower spruce proportion of 81% (Fig. 2). Thus, if the forest owner seeks to maintain high spruce proportions, establishing mixed stands may be favorable to increase returns, while buffering economic risks. It should also be noted that pure spruce stands still

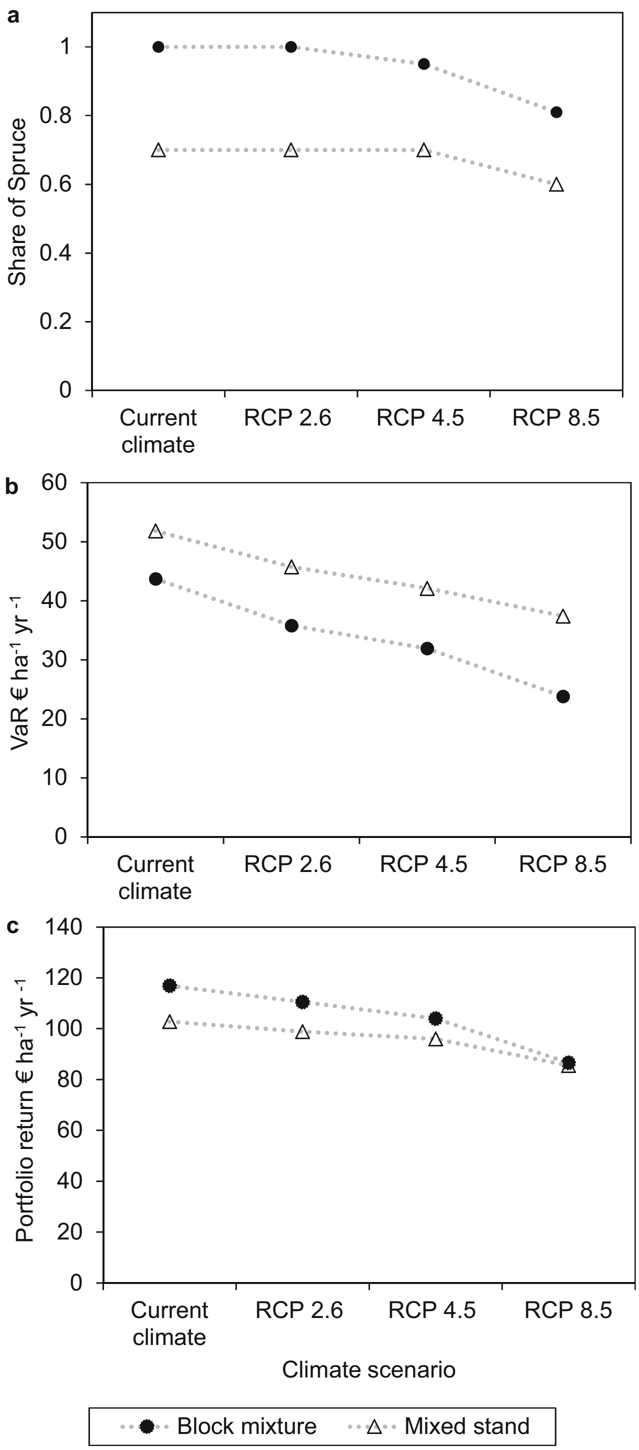

Fig. 3 Effects of climate change on economically optimal species portfolio (**a**), its respective maximized value at risk (VaR) (**b**), and portfolio return (**c**). The optimal forest composition refers to the optimized portfolio weights (see Eq. (3)) for block mixtures (circles) and the simulated tree mixtures with the highest VaR under different climate scenarios (triangles) (see also ESM Tables S11–12). The effect of climate change refers to altered survival probabilities (Fig. 2)

gave the highest expected returns but not the highest VaR, compared to all types of mixtures. This is despite the positive effect of mixture on stand stability and tree growth of spruce. Hence, a risk-neutral profit-oriented person would still chose to plant pure spruce stands even when considering the expected losses, due to stand failure (see ESM Tables S10 and S11).

Figure 3a also shows that species selection in mixed stands was more stable under rather extreme climate change scenarios. The optimal share of spruce decreased by 10 percentage points under the most extreme (RCP 8.5) climate scenario compared to the current climate. In the block mixture, species selection was already affected under the moderate RCP 4.5 scenario. Here, the ideal spruce proportion decreased by 20 percentage points for the RCP 8.5 scenario. Yet, the absolute spruce proportion remained for all scenarios still lower for the mixed stand compared to the block mixture.

Being aware of the high prediction error of climate variables on survival time of beech, we also calculated species portfolios that excluded climate change effects for beech. Under this assumption and applying the most severe climate change scenario to spruce, we found that portfolio composition did not change for mixed stands (60% spruce), while the spruce proportion of block mixture dropped to similar levels of 57%. The ideal share of spruce would only fall below 50% if survival of beech, in terms of $S(100)$ (at constant α), was by 45 percentage points higher than that of spruce. For our model, there was no combination within the different climates that could describe such a difference. Thus, even when considering increasing hazard rates in regeneration decisions, a risk-averse forest owner at our study site would opt for establishing stands that are dominated by the more susceptible tree species.

3.4 Sensitivity analyses

Differences in upfront investment costs are a classic driver of investment decisions. In our sensitivity analysis, changes in the establishment costs of spruce, relative to beech by ± 75% (i.e., ± 1500 €), reduced the share of spruce in optimized block mixtures from 100% to only 50% (Fig. 4). This difference in species selection is much larger compared to the simulated effects of climate change. It should be noted that in our baseline assumption, planting costs of beech are assumed to be by 50% higher compared to that of spruce. A relative increase in costs of spruce establishment compared to beech could result from subsidies for forest conversion towards broad-leaved species.

Establishment costs were also found to be a key decision criterion for selecting the optimal type of mixture. While, for our baseline assumption, mixed stands were shown to give a higher VaR compared to block mixtures, this advantage was reduced when assuming higher

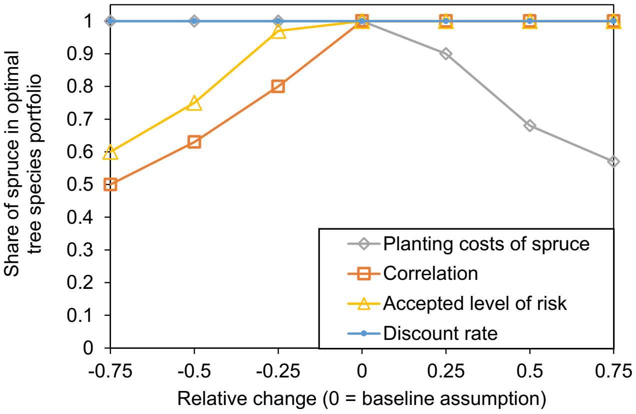

Fig. 4 Sensitivity analysis of further economic drivers of species selection. Results are shown for block mixture. Baseline assumption corresponds to current climate. Absolute values range between 500 and 3500 € ha^{-1} for establishment costs of spruce (while keeping those for beech constant), − 0.75 to + 0.75 for the coefficient of correlation between economic return (i.e., expected annuity) of beech and spruce, 0.4 and 2.6% for the discount rate, and 0.01 to 0.08 for φ (Eq. (2)), representing the accepted level of risk

establishment costs for mixed stands compared to block mixtures. Higher establishment costs could occur, due to the higher complexity, which may result in higher labour costs for stand establishment. In our data example, assuming the planting costs for beech (3000 € ha^{-1}) for all mixed stands clearly reduced their economic advantage (ESM Fig. S3). Under this assumption, pure spruce stands would outcompete mixed stands in terms of VaR. This finding supports the importance of establishment costs in forest investment decisions.

In terms of biophysical interactions, we assume that stand failure, i.e., hazard events for beech and spruce occur independently of each other. Given the anticipated increase in extreme weather events stand failure may become more intensively correlated (e.g., through drought or storm events). When testing a perfect correlation of events (reflected by the equal random number in the simulation process), we found a coefficient of correlation of return of 0.45 compared to 0.006 estimated under the baseline assumption. Thus, the high coefficient of correlation displayed in Fig. 4 might be rather unrealistic and not directly comparable to the relative change of other input variables. Yet, the results demonstrate that under a higher correlation of events, the advantage of having beech in the species portfolio will, by trend, be reduced.

Changing the accepted level of risk by decreasing the accepted shortfall probability from a moderate value of 5% to a very risk-averse value of 1% resulted in a 57% smaller optimal proportion of spruce in the block mixture. A moderate change in discount rate did not alter species selection in the block portfolio, when keeping other assumptions constant. Even under very low discount rates beech still could not compete with spruce in our data example.

We found that the optimal species composition in mixed stands was less sensitive to changes in model assumptions. The optimal spruce proportion did not drop below 60% (under current climate) when increasing establishment costs of spruce by 75% or decreasing shortfall probability to 1% (therefore not shown in Fig. 4). Only for an increase in discount rate to 2.6% did the spruce proportion increase to 80%. This reveals that biophysical interactions dominated species selection in mixed stands, while ideal compositions were less susceptible to other input variables.

4 Discussion

In our study, we follow the suggestion of Littell et al. (2011) for the use of climate change modelling in resource planning, which states that "the role of models […] is not to predict the future exactly, but rather to narrow its possible range to a subset of plausible outcomes that identify the vulnerability of specific resources and suggest appropriate management" (Littell et al. 2011, p. 2). While we do not aim to make exact predictions or give precise recommendations for species proportions, we aim to use statistically backed plausible ranges of survival probabilities to investigate their economic effects on regeneration decisions.

Referring back to the first part of our central hypothesis, our results revealed a rather moderate effect of altered survival probabilities on economically optimal species selection. At our example study site, the more susceptible spruce remained the dominant species, even for the most severe climate change scenario. Given the limited time series available for the pan-European mortality data (ICP Level I and Level II data, ESM Tables S1 and S2) and the inherent assessment errors in the dataset (see also Neuner et al. (2015)), prediction errors on climate change responses are still large. Further uncertainty is due to the prediction of future climate variables by the selected circulation model (Littell et al. 2011), which we did not directly address. The estimated survival rates, particularly those for spruce, are, however, rather pessimistic compared to earlier studies. Examples of reported $S(100)$ values for pure stands (current climate) range from 0.69 (based on a literature review in Germany (Beinhofer 2009)) to modelled values of 0.8 for Southwest Germany (Griess et al. 2012) and 0.9, when applying the model by Neuner et al. (2015) to the study site. We corrected our analysis for left truncation, which may explain the lower level of survival compared to earlier studies. Our estimated values for beech fit well to data compiled by Beinhofer (2009) ($S(100) = 0.889$) and Staupendahl (2011) ($S(100) = 0.82$). The estimated relative effects of climate change are, for both species, also in the range of those found by Nothdurft (2013) (referring to mountainous areas in Southwest Germany) and Neuner et al. (2015). Thus, given the survival probabilities used here, it is rather unlikely that the survival probability of spruce is overestimated in relation to that of beech. By reporting the threshold for which spruce would lose its dominant position, our finding appears robust in face of climate change-related uncertainties.

Expected returns for spruce under climate change are probably rather conservative, as we also excluded further adaptation strategies, such as selection of plant material (Gray and Hamann 2011), thinning concepts, and optimal rotation age, which may not only increase economic performance (Bright and Price 2000; Möllmann and Möhring 2017) but also stand resistance of spruce (Bolte et al. 2009; Jandl et al. 2015). Our dataset suggested a rotation period of 90 years for spruce. Applying shorter rotation periods under the climate change scenarios might increase the economically optimal share of spruce in future tree species portfolios. Hence, the optimal spruce shares for our study site might be slightly underestimated. Future studies could combine both the economic consequences of species diversification and changes in rotation age (see for example Messerer et al. (2017) for a methodological example). Recent studies also suggest an increase in growth performance of spruce under climate change (Gutsch et al. 2016; Thiele et al. 2017), while larger scale species distribution models have anticipated a long-term shift from coniferous to broad-leaved species (Dyderski et al. 2017). We disregarded growth responses to climate variables. However, given the assumptions in our model (based on Clasen (2015)), the cumulative harvested wood volume over a period of 90 years (excluding hazards) was 875 m^3 ha^{-1} for spruce and 453 m^3 ha^{-1} for beech. Thus, in order to compete with spruce, growth volume of beech would have to at least double, given the lower quality and wood price. Yet, the inclusion of growth effects should be considered in further studies, to allow for a trade-off analysis between growth and hazard effects (e.g., Thiele et al. (2017)).

Concerning the second part of our research hypothesis, we found that the type of mixture affected the economically ideal species compositions. Horizontal heterogeneity could also buffer but not completely mitigate the economic consequences of climate change for a risk-averse forest owner. Using the VaR as criterion for economically optimal species composition, mixed stands were more effective in buffering the effects of climate change compared to block mixtures. Yet, in terms of expected returns, pure spruce stands would still outcompete any form of mixture in terms of return for all climate scenarios. Ideal (and thus recommendable) species composition in mixed stands was also more robust in the direction of perturbations in expected survival probabilities compared to that of block mixtures. Thus, mixed stands offer a hedge against uncertainties in future predictions. This finding depends, however, on the biophysical interactions assumed. In our statistical model, the effect of mixture was selected as a linear effect on survival time by the statistical selection procedure, which should be interpreted with caution. Alternatively, Roessiger et al. (2013) assumed that lowering the spruce proportion below 49% would not achieve a more intense stabilization compared to a proportion above this threshold. Our estimated effect of mixture on species resistance appears, however, plausible. For example, Knoke and Seifert (2008) assumed a similar increase in $S(100)$ of spruce from 0.53 in pure stands to 0.81 in mixed stands. Evidence on mixture effects on beech are rare, while available studies point towards positive impacts on stand resistance (Metz et al. 2016; Pretzsch et al. 2010) and no adverse effects on timber quality (Benneter et al. 2018). In our data example, mixed stands would still outcompete block mixtures by 17% in terms of VaR (under constant climate) when excluding the stabilizing effect of species mixture on beech. The assumed effects of mixed stands on timber quality and wood volume hardly influenced the objective function of our analysis. Excluding the factors given in ESM Table S8 led to a slight increase in the VaR of the optimal species portfolio by 2% (53 € ha^{-1} $year^{-1}$), as the assumed negative effects of mixture on timber quality and volume growth of beech are disregarded. This small change did also not affect the optimal species proportions in the mixed stand portfolio. Yet, we found that decisions on the type of mixture will also strongly depend on the differences in establishment costs between them, which have seldom been systematically studied.

Diversification in mixed stands is not restricted to horizontal heterogeneity alone. Vertical heterogeneity was not considered in our study, given our focus on regeneration planning subsequent to a regional storm event. However, fostering uneven-aged forests will also offer advantages in terms of time diversification (Couture et al. 2016; Messerer et al. 2017; Roessiger et al. 2013) and aspects of flexibility—as considered in real option approaches (Schou et al. 2012; Schou et al. 2015), while further increasing stand resistance (Díaz-Yáñez et al. 2017). In our study, we refer to adaptation to climate change by adjusting species selection of future forest generations. This decision is mainly driven by economic considerations and the risk attitude of the decision-maker. This perspective uses a static approach of infinity, meaning that if the forest owner suffers from stand failure, the initially chosen tree composition will still be used for regeneration. This assumption appears plausible as future tree generations partly stem from natural regeneration (see ESM Table S7). However, changing information on climate change may update knowledge and beliefs and change decisions in the future. Using our simulation results for informing a Bayesian simulation approach (Yousefpour et al. 2014, 2017) could be a fruitful field for future research.

We found that economic input parameters, such as establishment costs, discount rates, or correlations, affected species composition at a similar magnitude compared to climate change, thus supporting and extending the findings by Neuner and Knoke (2017). This result should, by no means, undermine the importance of adaptation strategies towards climate change. But, it demonstrates that regeneration strategies for climate-smart forestry should still carefully consider classic drivers of investment decisions, particularly establishment costs. We found that optimal species proportions in mixed stands were more robust towards perturbations in these drivers. Hence, mixed stands might offer an important hedge against both climate and market uncertainty.

In our study, we identified optimal species mixtures according to the VaR criterion. This criterion corresponds to the objective of avoiding situations with very low return expectations. This is a rather conservative measure of portfolio selection, which may be applicable for the management of natural resources (Härtl et al. 2013). In line with classic portfolio theory, the approach is based on the assumption of normally distributed returns, which may not always be met, particularly under the occurrence of rather extreme events (Fasen et al. 2014). It is furthermore a very data-intensive approach, as expected returns, risks, and correlations between alternatives are derived from the Monte Carlo simulation. In situations with scarce data and non-normally distributed returns, robust portfolio optimization techniques may offer an alternative approach (Knoke et al. 2017; Messerer et al. 2017).

Our approach could be further extended and improved by a larger number of species (Brunette et al. 2017), for which survival functions are currently under development. This could substantially change the proportion of spruce for our example site, particularly when including more economically competitive species, such as Douglas fir (Beinhofer and Knoke 2010; Knoke et al. 2017). Furthermore, economic considerations may not be the only drivers of regeneration decisions, while provision of multiple ecosystem services might further support the establishment of mixed stands rather than pure stands or block mixtures (Knoke et al. 2017).

5 Conclusions

The bio-economic modelling approach reveals that survival probabilities are a crucial aspect to consider in regeneration planning. This finding also underlines the economic relevance of empiric tree survival modelling and the importance of continuous tree mortality observations, such as those available from the ICP Forest or the German crown condition databases. Continuing and expanding this monitoring network will improve future bio-economic modelling approaches. Particularly, the effects of stand mixtures on stand resistance are of high economic importance.

Our findings also support current policies towards incentivizing mixed stands. Mixing species may be an important measure to increase forest stability, while also maintaining high shares of economically desirable species. This applies, for example, to spruce in Central Europe with its high importance for the wood-processing industry. Our results also demonstrate that incentives related to establishment costs may impact the forest owner's regeneration decisions more intensively than expectations on increasing natural hazards.

Our approach combines an empiric and mechanistic model and builds on sensitivity analysis. Understanding and communicating the economic consequences of uncertain input factors can help to design purposeful adaptation strategies and regeneration planning.

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Statement on data availability All biophysical and economic input coefficients to reproduce and further apply our bio-economic model are provided in the Electronic Supplementary Material. The original tree mortality data used for parametrization of the statistical model is available from the International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (www.icp-forest.net), and climate data is freely available from the WorldClim database (www.worldclim.org). Model codes are available from the authors upon request.

Compliance with ethical standards

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

Appendix

Table 1 Coefficients derived from AFT-fitted Weibull distribution to predict survival probability of spruce and beech based on the European dataset

Covariate	Coefficient	SE
Spruce		
Share of spruce	0.719	0.055
Sum of precipitation of warmest quarter	− 0.001	0.000
Mean temperature warmest quarter	0.066	0.008
$\ln(\beta^{a})$	6.229	0.159
$\ln(\alpha)$	0.259	0.020
Beech		
Share of beech	0.577	0.012
Minimum temperature in coldest month	− 0.039	0.016
Maximum temperature warmest month	0.089	0.105
$\ln(\beta^{a})$	8.179	0.402
$\ln(\alpha)$	0.241	0.051

Exp(Coefficient) is the acceleration factor. It corresponds to the ratio of survival times to any fixed value of $S(t)$. An acceleration factor greater (less) than one indicates that the covariate decreases (increases) time to death. Thus, a positive coefficient translates to an acceleration factor > 1, i.e., the effect on survival of the respective variable is negative. The entire model written in R language is available from the authors upon request

SE standard error of coefficient

[a] Scale parameter is reparametrized for different values of coefficients using the following formula:

$$\beta_{\text{reparametrized}} = \frac{\beta}{\exp(\text{coef}1 \times x1) \times \exp(\text{coef}2 \times x2) \times \exp(\text{coef}3 \times x3)}$$

where coef denotes the coefficient and x the value of the corresponding explanatory variable. See ESM Table S9 for scale parameters derived for the study site

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