Alternative forest management strategies to adapt to climate change: an economic evaluation for Germany

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Abstract

Since the year 2018, the yield and management situation in German forest enterprises is characterized by extreme weather events (storms, draught) and, consequently, bark beetle calamities, leading to a significant above-average occurrence of damaged timber. In addition to processing the damaged timber, forest managers are challenged to develop and implement silvicultural adaptation strategies to climate change in order to ensure future wood production and long-term viability of these enterprises.

In our study, we aimed to estimate the long-term economic impacts of an active climate change adaptation strategy compared to a passive, successional adaptation strategy on the forestry sector under consideration of climate change induced survival probabilities, using – and enhancing – the Forest Economic Simulation Model (FESIM).

Based on our study's assumptions about tree species changes, we find that active forest conversion demands greater initial financial investment. However, in the long run, it proves to be economically more sustainable despite persistent risks. This is due to the potential for higher growing stock, felling volume, and ultimately improved yields in the future. The findings from our analysis offer valuable insights and decision-making guidance for both forest enterprises and forest policy, regarding the two adaptation strategies.

Key words: forests, management strategies, climate change adaptation, economic impact

Zusammenfassung

Seit dem Jahr 2018 ist die Ertrags- und Bewirtschaftungssituation in deutschen Forstbetrieben durch extreme Witterungsereignisse (Stürme, Trockenheit) und in der Folge durch Borkenkäferkalamitäten geprägt, die zu einem deutlich überdurchschnittlichen Schadholzaufkommen führten. Neben der Aufarbeitung des Schadholzes sind die Waldbewirtschafter gefordert, waldbauliche Anpassungsstrategien an den Klimawandel zu entwickeln und umzusetzen, um die zukünftige Holzproduktion und die langfristige Überlebensfähigkeit der Forstbetriebe zu sichern.

Ziel unserer Studie war es, die langfristigen wirtschaftlichen Auswirkungen einer aktiven Anpassungsstrategie an den Klimawandel im Vergleich zu einer passiven, sukzessiven Anpassungsstrategie auf den Forstsektor unter Berücksichtigung von klimawandelbedingten Überlebenswahrscheinlichkeiten abzuschätzen.

Auf der Grundlage der in unserer Studie getroffenen Annahmen über Baumartenveränderungen stellen wir fest, dass die aktive Waldumwandlung anfänglich höhere finanzielle Investitionen erfordert. Langfristig erweist er sich jedoch trotz anhaltender Risiken als wirtschaftlich nachhaltiger. Der Grund dafür ist das Potenzial für einen höheren Holzvorrat, ein höheres Einschlagsvolumen und letztlich bessere Erträge in der Zukunft. Die Ergebnisse unserer Analyse bieten sowohl für die Forstbetriebe als auch für die Forstpolitik wertvolle Erkenntnisse und Entscheidungshilfen für die beiden Anpassungsstrategien.

Schlüsselwörter: Wälder, Bewirtschaftungsstrategien, Anpassung an den Klimawandel, wirtschaftliche Auswirkungen

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1 Introduction

1.1 Consequences of climate change and its impact on forestry in Germany

In the last years, severe weather and climate events occurred ever more frequently in Europe (EEA, 2019), causing large-scale forest fires, heavy rainfalls, destructive storms and persistent draughts.

In Germany and other central European countries, a presumably climate change induced close succession of storms, periods of drought and following bark beetle pests since 2018, has led to a high proportion of mortality in the forest stands, especially of spruce stands, that needed to be processed quickly, and finally to a collapse of timber market. In total for Germany, up to the end of the year 2020, the economic damage of these events in the forest sector were estimated to be more than 12.75 bn Euro, with an area to be reforested of around 284,000 ha. The total amount of damage for the years 2018 to 2020 in Germany amounted to ten times the annual net income of the forestry sector and an amount of damaged wood of 176.8 million m³ almost reached the magnitude of three years of regular annual fellings (Möhring et al., 2021). As a financial support to forest owners, about 1.5 bn Euros of subsidies and aid programs were shortly enacted by the Federal Republic of Germany and its states (BMEL, 2021).

The consequences of climate change as well as the need for mitigation and adaption has been recognized by the EU and the German government. Measures and objectives for adaptation are defined *e.g.* in the New EU Strategy on Adaptation to Climate Change and the Climate Target Plan 2030 (European Commission, 2020a, 2021a). Moreover, the EU Forestry Strategy 2030 recognizes the necessity of transitioning forests to encompass more climate-resilient species (European Commission, 2021b). Simultaneously, the EU Biodiversity Strategy 2030 emphasizes the crucial role of safeguarding and rehabilitating carbon-rich ecosystems in the battle against climate change (European Commission, 2020b). In Germany, the respective future national strategies will presumably reflect the EU strategy's underlying aims. The Scientific Advisory Board for Forest Policy of the Federal Ministry of Food and Agriculture (BMEL), for example, also emphasizes the need to adapt forests and forestry to climate change (WBW, 2021). With the current amendment of Germany's Joint Task for the Improvement of Agricultural Structures and Coastal Protection (GAK), site adapted forestry measures will be promoted (BMU, 2016).

The authors of this study assume, that under the current global political frame conditions climate change mitigation measures will not limit global warming completely. If the emission of greenhouse gases continues, a continuation of global warming and extreme weather events is expected. The increase in global surface temperatures is likely to surpass 1.5 °C in all Representative Concentration Pathway (RCP)-scenarios (IPCC, 2014). The climate change-related forest damages are expected to further impact forestry in the future (Lindner et al., 2010; Spellmann 2020; Bolte et al. 2021). In particular, the main timber species spruce, pine, beech and oak will be subject to a strongly increased mortality risk on their current growth sites in Germany. Likely, there will be many areas where cultivation of the present main tree species is no longer profitable (Teuffel, 2019). According to Spellman's research (2020), the percentage of forest areas in Germany that are considered to have low drought stress risk for spruce is projected to decline significantly, from approximately 100 % (average between 1981 and 2011) to just under 41 % by 2060 (average between 2041 and 2070). In contrast, the proportion of forest sites with high drought stress risk is expected to rise from less than 1 % to around 26 %. A comparable development is also predicted for beech, while the forecast for oak, Douglas-fir, and pine is somewhat more favorable, although increased drought stress risk is also predicted for these main tree species. Bolte et al. (2021) state similar figures with 70 % of spruce-dominated stands and 30 % of beech-dominated stands being at risk.

In summary, forestry today is confronted with fundamental choices in the face of climate change and increasing risks, requiring long-term economic assessments of alternative courses of action. Due to the long-life cycles of forests the possible observation and assessment of all consequences of a silvicultural decision and its realization can take decades or even centuries (Oesten and Roeder, 2002) and are hardly depictable in their complexity.

Therefore, the consequences of a silvicultural decision on natural and economic key figures are best made visible by means of model-simulations and analyses (Oesten and Roeder, 2002; Rosenkranz et al., 2014; Dög et al., 2016; Möhring and Dieter, 2020).

Analyses of the consequences of climate change for forest management have been a very important field of research in German forest sciences. This can also be seen in the large number of practical and scientific publications. The primary emphasis in this context lies particularly on ecological(Ding et al., 2016; Yousefpour et al., 2017), silvicultural (Hanewinkel et al., 2010; Berendt et al., 2017; Eichhorn et al., 2016), and forest health issues (Albert & Schmidt 2012; Albert et al., 2015, 2017, 2018; Fleck et al., 2015; Brandl et al., 2020), while also addressing various adaptation strategies and their implications on natural key figures (Duda, 2006; Bolte et al 2009a, 2009b; Kölling et al., 2009; Milad et al., 2012; Albert et al., 2015; Yousefpour et al., 2017; Oehmichen et al. 2018; Jandl et al., 2019). In economic forest science, consequences of climate change for forest management have not yet been addressed with the same intensity in Germany and/or Central Europe. Although there have been studies quantifying the costs of damages and reduced yields from climate change (*e.g.* Möhring et al., 2021), estimations and analyses of long-term economic consequences of different adaptation strategies using modeling techniques are scarce. Olschewski et al. (2008) and Ding et al. (2016) use economic models but assess the consequences for overall forest ecosystem services. Oehmichen et al. (2018) compare different climate change scenarios in regard to their future impacts on forestry, however, their research is limited to the consequences for wood supply without including economic data. While Paul et al. (2019) include this data in their study, they do not compare different scenarios and thus do not evaluate different adaptation strategies. Pauli (2014) models the consequences of several adaptation strategies on yield and risks of forest production for a case-study region of Switzerland, also including economic data. The analysis primarily focuses on the associated costs and lacks substantial consideration of the potential yields or benefits. Hanewinkel et al. (2012) estimate a reduction of the economic value with the land expectation value for three different tree species groups, interest rates and climate scenarios for the years between 2011 – 2100 using the European Forest Information Scenario model (EFISCEN). However, the model does not cover change of adaptation strategies in forest management, nor a risk for calamity.

It becomes clear, that significant shifts in the future proportions and distribution of the main tree species can be expected and a conversion of forests towards climate change adapted species will become necessary (Teuffel, 2019; Spellmann, 2020; Bolte et al., 2021). With this in mind, it is plausible to consider two contrasting strategies that could potentially help clarify the issue at hand: i) actively planting climate change-adapted species at high investment costs, thereby determining the future tree species composition. However, this endeavor also entails the entrenchment of capital over an extended duration, or ii) purposefully omitting investment costs and rather counting on natural succession of regeneration areas (Bolte et al., 2009a; Kolström et al. 2011; Jandl et al. 2019). To address the long-term economic consequences with a complex risk description, a dynamic model with an included risk function is needed.

1.2 Research objective

In view of the impact of climate change on German forestry as well as the current EU and national policies and strategies for the adaptation to and mitigation of climate change, we defined the following research question:

What are the long-term economic impacts of the active climate change adaptation strategy of a forest conversion towards climate-change adapted tree species to the passive, successional adaptation strategy of relinquishing calamity areas to succession on the forestry sector?

We identified and assessed natural and economic impacts of two contrasting forest management adaptation strategies to climate change for forestry in Germany, using a forest-economic simulation-model. With our case study, we hope to provide information and decision-making support for forest managers and forest policy in their current actions regarding future climate-adapted forest management. To depict a sectoral perspective our scenario simulations were carried out for a “German Forest Enterprise”, including the total German forest area and average silvicultural and economic input data. For our simulation we recognize multifunctional forestry as a legal requirement in Germany. Further, we omit simulations towards optimizing raw wood production or profitability. In our evaluation we focused on business economic impacts and the economic appraisal of timber production as an ecosystem service and a private good. Other ecosystem services and public goods, *e.g.* nature conservation issues and societal welfare gains and losses, were not part of the study. Also, implication in regard to climate change mitigation, like *e.g.* the CO_2-sequestration in forests was not assessed.

2 Methods

2.1 Scenario development

For our methodological approach, we created the “high intensity adaptation” (HIA) and the “low intensity adaptation” (LIA) scenario with contrasting forest adaptation strategies to climate change. Further, we created a “business as usual”-scenario (BAU), depicting the previous forest management with little impacts of climate change, as a reference for orientation.

i) In BAU we assume, that everything in the German forestry sector will continue as if climate change only had a negligible impact, as it was the case in previous decades. BAU is therefore calculated based on the RCP 2.6 (IPCC, 2014). The tree species composition changes for BAU are equal for final harvesting and unplanned calamity fellings. They were derived from the tree species changes between NFI 2002 and NFI 2012, which were perpetuated to the future (Appendix A, Table 1). As the authors deem a long-term development after the BAU-settings as unrealistic, the BAU-results are shown only for in short-term for the first simulation period.

ii) In the HIA-scenario an active approach of forest management is represented: designated site-suitable tree species are selectively planted after calamities and also after final felling to actively increase the resilience of the forest to climate change, and to provide reliable yields in the future. Thus, the forest owners actively invest in a change of tree species composition on the entire forest area, regardless of whether the harvest was planned or unplanned.

iii) In the LIA-scenario, on the other hand, forest owners who have partly retracted from active forest management as a result of the rapidly increasing forests damage from climate change induced calamities are represented. The assumed species transition after scheduled harvesting and after calamity felling therefore differs in this scenario. While the transition after scheduled harvesting corresponds to HIA, the calamity areas are largely left to natural succession. With this, we simulate the adverse situation, that forest enterprises are not always in the condition or willing to react comprehensively to large and severe calamities in their forests, especially in regard to the financial investment of replanting.

Both, LIA and HIA were modelled based on RCP 8.5 (IPCC, 2014). For the RCP 8.5 climate scenario, an increase in average temperature, a decrease in average precipitation and a deterioration of the climatic water balance in the coming decades for Germany is expected, leading to increased drought stress risks for the German forest tree species (Moss et al. 2010; IPCC, 2014). In result, i) forest-sites are deemed to be rendered unsuitable for the present stock of tree species, resulting in species drifts, and changes in tree species composition, whereas ii) survival probability in the remaining stands is deemed to be reduced.

Impacts on the tree species composition in the HIA- and LIA-scenario, were integrated in the simulation in the form of a transition matrix as shown in Appendix A (Table 2), based on the recent scientific research of Spellmann (2020). This table shows to what extent in percent the original area of each tree species (in columns) is regenerated with the same or other species after regular and calamity felling (in lines). In our scenarios, the area percentages that were classified by Spellmann (2020) to be at high and medium drought stress risk for the respective tree species in the future were considered, rounded to the next step of five. We assumed, for example, that 40 % of the original spruce area remains stocked with spruce species, whereas 60 % changes to other, more climate adapted tree species (Appendix A, Table 2). As we used tree species as representatives for whole tree species groups in our simulation (Table 1) the values given by Spellmann (2020) were modified in some cases to account for site suitability of other tree species within the tree species groups. In the HIA-scenario, for calamity areas the same tree species composition is assumed to be planted on areas with regular final fellings, with the exception of birch, which is assumed to remain birch after calamities. In the LIA-scenario the calamity areas left to succession (natural regeneration) are assumed to mainly convert to birch (as a representative for other short-lived, successional species) with a smaller share of the area assumed to naturally regenerate with the previous tree species, whereas areas which were stocked with birch are assumed to regenerate again only with birch. In the simulation, tree species changes on regular felling areas in our simulation occur just until the striven tree species area shares are reached, while on calamity areas, natural succession proceeds continuously over the entire simulation period (“once birch, always birch”) as it is presumed that climate change will not abate in the short- or mid-term.

The changing survival probabilities of the remaining stands, were calculated in a climate sensitive manner, based on the research of Brandl et al. (2020) (chapter 2.3).

For comparability, each strategy starts with equal forest conditions, based on the average tree species and age class composition from the German National Forest Inventory (NFI 2012). As we aimed to show the impact of different tree species composition under the influence of climate-change induced survival probabilities on the income situation of German forestry we assumed, that basic tree species specific economic settings and silvicultural management practices remain the same in all three strategies. Only the tree species composition changes differ within the adaptation scenarios. The calculated scenarios should not be interpreted as a definitive prognosis, but rather as potential projections of the selected key metrics based on the assumptions provided.

2.2 The forest economic simulation model

As the basis for our simulations, we used an enhanced version of the Strugholtz-Englert-Simulation Model (Strugholtz, 2010; Rosenkranz et al., 2014). This excel-based model simulates different forest management alternatives over a time-period of up to 200 years, based on adaptable input data for the tree species spruce, pine, Douglas fir, beech and oak. It can assist operational forest managers in decision-making processes, by showing the long-term natural and economic effects of silvicultural management options. Further, the model allows to calculate the opportunity costs of atypical forest management activities such as, *e.g.* the implementation of nature protection requirements (Rosenkranz et al., 2014; Rosenkranz and Seintsch, 2015; Rosenkranz and Seintsch 2017) or the provision of protective and recreational forest-functions (Dög et al., 2016). The model can be described as a multi-input model, which consists of

- a forest-growth model, based on parameterized yield tables from Smaltschinski (2001),
- a forest management model, based on variable settings for parameters such as *e.g.* intended age structure, future tree species area composition on regular felling areas, number of trees planted, thinning practices, type of harvesting and rotation cycles,
- survival probabilities, implemented by means of tree species specific Weibull probability distributions, as *e.g.* suggested by Staupendahl and Möhring (2011) and
- an economic evaluation model (financial-mathematical calculation of the economic key figures based on revenues from thinning/harvesting in combination with assortment tables).

The model does not focus on individual stands, but on age classes for different enterprises or regions. It provides a simulation of utilization measures with simultaneous updating of the timber stock and an economic analysis of the production processes (Strugholtz, 2010). At the end of each rotation cycle the forest is regenerated according to an adaptable tree-species-conversion-matrix. For results, the model calculates, *e.g.* tree species compositions, age class distributions, growing stock, timber fellings, silvicultural contribution margins (SCM= revenues from timber harvesting less felling, planting and pre-commercial thinning costs) and net present values. The net present value is calculated as the discounted contribution margin over the 200-year simulation periods, plus the discounted stand liquidation value at the end of the observation period. In our study we used an interest rate of 1.5 % for the dynamic calculation, derived from Möhring (2001). Further explanations on model functions can be found in Seintsch et al. (2012) and Rosenkranz et al. (2014).

In order to enable climate-sensitive modelling, several advancements had to be made to the model. In the course of the enhancement process, the model was renamed to Forest Economic Simulation Model (FESIM). As a central development, it was extended to allow the incorporation of climate-sensitive changes in survival probabilities.

This was implemented by using climate-sensitive Weibull scale parameters, based on the survival probability models by Brandl et al. (2020) as input parameters. Analogously to Fuchs et al. (2021), in each simulation step, the total drop-out of each stand was defined deterministically by the calculated survival probabilities from the Weibull distribution. The climate parameters required for the calculation of the Weibull parameters were taken from the WorldClim 1.4 data base (Hijmans et al., 2005) for the year 2070, which is the latest possible date of this data base. For the coordinates of the climate variable, a climate measuring station which is close to the geographic center of Germany was exemplarily used.

In a next step, the complexity of the model was extended with the possibility to distinguish regeneration practices for regular final fellings areas as well as for calamity areas, thus offering the possibility to include differentiated climate change adaptation strategies. Further, an adaptable factor for the amount of unutilized timber remaining in the forest after calamities was included and the tree species birch, as a representative for all other successional and for short-lived deciduous tree species was added. This novel species was used as a species alternative in the LIA-scenario after calamities. Consequently, within the FESIM framework, six tree species have been incorporated, serving as representatives of distinct tree species groups and treated as theoretical monocultures (Table 1). For simplification, only the representative tree species (spruce, pine, Douglas fir, beech, oak and birch) are mentioned in the following text. With our settings in FESIM we indirectly considered the changed suitability for cultivation as a result of climate change. This was achieved by settings for the subsequent stands in the model, based on Teuffel (2019) and Spellmann (2020). As a climate sensitive change in forest growth cannot be modelled with FESIM yet, we assumed, that the tree species on their future suitable sites have a similar forest growth as on suitable sites to date. Thus, with incorporation of climate-sensitive changes in survival probabilities, we have contributed to improving climate-sensitive modelling, but do not claim to be able to comprehensively model in a climate-sensitive manner.

Table 1: Representative tree species of the Forest Economic Simulation Model

Tree species	Representative for
Spruce	all spruce and fir species (Picea spec and Abies spec.)
Pine	all pine and larch species (Pinus spec. and Larix spec.)
Douglas fir	Douglas fir (Pseudotsuga menziesii) and all other fast-growing, neophytic coniferous species
Beech	beech and all deciduous tree species of high longevity except oak (*e.g.* maple (Acer spec.), lime (Tilia spec.), ash (Fraxinus spec.) and others)
Oak	all Oak species (Quercus spec.)
Birch	all deciduous species of low longevity (*e.g.* birch (Betula spec.), aspen (Populus tremula), willow (Salix spec.) or rowan (Sorbus aucuparia))

Source: NFI 2012

2.3 Data base and assumptions

As a data source for the forest area in 2012 and the respective tree species composition, the accessible, stocked, tree species area per age class of the entire German Forest was taken from the National Forest Inventory (NFI, 2012). Here, we used the 10.6 million ha of accessible and stocked forest area. However, we did not attempt to update the NFI data, *e.g.* in regard to forest damage. Further average economic and natural input data was taken from recent studies and official data from the BMEL, as for example, the Forest Accountancy Data Network (FADN). Where no citable data could be found, qualified assumptions within the studies' consortium were made (*e.g.* in regard to the share of used calamity timber, the costs for thinning and the initial number of trees planted for regeneration). The basic data, is shown in Table 2, comprising silvicultural and economic as well as risk related input data.

Table 2: Input data for the Forest Economic Simulation Model

	Spruce	Pine	Dgl. fir	Beech	Oak	Birch	
Silvicultural input data							
Number of stems/ha after regeneration	2,500	8,000	2,500	7,000	6,000	6,000	Dög et al., 2016
Production period (median)[1]	120	140	120	160	180	70	BMEL, 2016
Factor of utilized timber from calamities[2]	0.8	0.8	0.8	0.8	0.8	0.8	own assumption
Economic input data							
Costs of regeneration for same tree species after regular felling (Euro/ha)	1,300	1,900	1,400	1,800	2,600	0	MELV, 2015; HessenForst 2019 (unpub.); MULE, 2019
Costs of regeneration for changing tree species after regular felling (Euro/ha)	4,300	5,800	5,200	10,200	16,500	0	
Costs of regeneration after calamity in (Euro/ha) (HIA)	5,100	7,500	6,500	12,400	18,900	0	
Costs of regeneration after calamity in (Euro/ha) (LIA)	1,300	1,900	1,400	1,800	2,600	0	
Pre-commercial thinning costs (Euro/ha)	500	500	500	500	500	25[3]	
Calamity-induced shortfalls in revenue[4]	-45 %	-20 %	-45 %	-20 %	-10 %	-15 %	Möhring et al., 2021
Calamity-induced additional expenses	+15 %	+15 %	+15 %	+15 %	+15 %	+15 %	
Interest rate	1.5 %	1.5 %	1.5 %	1.5 %	1.5 %	1.5 %	Möhring, 2001
Average felling costs in EUR/m^3	24.7	24.7	24.7	24.7	24.7	24.7	BMEL, 2022
Average timber prices in EUR/m^3	78.4	62.6	78.4	58.0	95.0	30.0	
Risk related input data							
Factor of survival after 100 years: BAU	0.49	0.73	0.81	0.77	0.66	0.66	IPCC, 2014 Brandl et al., 2020
Factor of survival after 100 years: LIA & HIA	0.31	0.62	0.76	0.69	0.44	0.44	

Sources: BMEL (2016), BMEL (2022), Brandl et al. (2020), Dög et al. (2016), HessenForst (2019, unpub.), IPCC (2014), MELV (2015), Möhring (2001), Möhring et al. (2021) MULE (2019) and own assumptions

The costs of regeneration are based on mean values calculated from the forest valuation guidelines of the German Federal States of Lower Saxony and Saxony-Anhalt and information from the Hessian Forest Valuation Service Agency (MELV, 2015; HessenForst, 2019 (unpub.); MULE, 2019). They apply to successful and secured regenerations. When no transition of tree species was simulated, we implied natural regeneration at low costs. For artificial regeneration, fencing was assumed on 10 % of the regeneration area for the spruce, 20 % for Douglas fir and beech and 80 % for oak. Fencing costs were assumed to be 7,200 Euro/ha including material, control and

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[1] In Germany, clear-cutting as a final use is predominantly only permitted in exceptional cases and on small areas after approval by the authorities.

[2] The factor of utilized timber from planned final fellings describes the amount of timber harvested except unused coarse wood, not however from whole tree harvesting.

[3] The low value of pre-commercial thinning for birch shall depict, that some forest owners in Germany will certainly conduct extensive measures on birch on a small local area share.

[4] These figures are derived from a current study of Möhring et al. (2021) who used controlling results of one large private, communal and state forest enterprise as a basis for the markdowns.

removal. For the LIA-scenario we assumed that economic activities after calamities were focused only on small area shares, therefore the costs of regeneration after calamities in the LIA-scenario are to equal the low costs of regeneration for same tree species after regular felling.

For our simulations we assumed, that the stocked and accessible German forest area remains constant over the 200-year simulation period. Further, as the model does not (yet) allow for calculation changing revenues and prices, and also because no predictions over the change of timber felling prices and revenues can be made, we assumed constant values as well. As no timber revenues for birch could be retrieved from the FADN we assumed timber revenues before deducting felling costs of 30 Euro/m³. Additionally, we implied no planting costs for birch as we treat it purely as a species of natural succession. For the two scenarios as well as the BAU we calculated with the same natural and economic input data (Table 2). We only changed the future tree species composition for each strategy, therefore being able to show the effects of changing adaptation measures.

3 Results

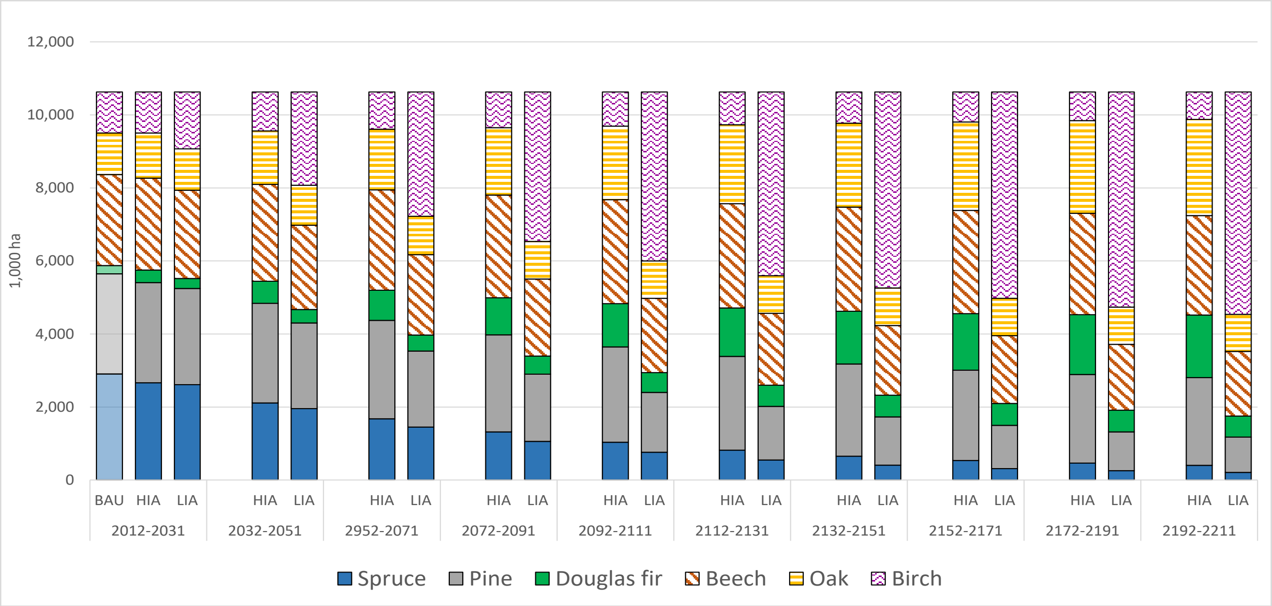
In the following, the results from the simulation for the LIA- and HIA-scenario, over the entire simulation period of 200 years and comprised to average values of ten 20-year periods, are described. Hereby, the BAU is intended to serve as an initial orientation for previous forest management without (significant) adaptation to climate change and is therefore only shown for the first 20-year period. The simulations start with the same initial values and settings. As tree species changes start occurring in the first period, average values for all key figures in this period could vary.

For each scenario, the tree species area distribution, growing stock and timber fellings, as well as the standing timber value, the silvicultural contribution margin (SCM= felling revenues less felling, planting and thinning costs) and the net present values were calculated for a period of 200 years and compared to each other. All presented simulation results for the scenarios can also be found in Tables B.1-B.6 in Appendix B.

3.1 Tree species composition change and costs for regeneration

Figure 1 shows the tree species composition differences between the LIA- and HIA-scenario. In the HIA-scenario, spruce undergoes the biggest area loss with 21 % in regard to the total forest area and 85 % in relation to the original spruce area. The highest increase in regard to the total forest area is accounted to Douglas fir and oak, both increasing by 13 %. In the LIA-scenario, birch increases by 43 % in relation to the entire forest area, due to the assumed abandonment of calamity areas to natural succession. In this scenario, Douglas fir is the only other species gaining area, by means of climate change adapted regeneration after regular felling. Thus, the loss of dominance of spruce and pine and the shift towards Douglas fir and deciduous species becomes visible in both scenarios, whereas the change towards birch is especially revealed in the LIA-scenario.

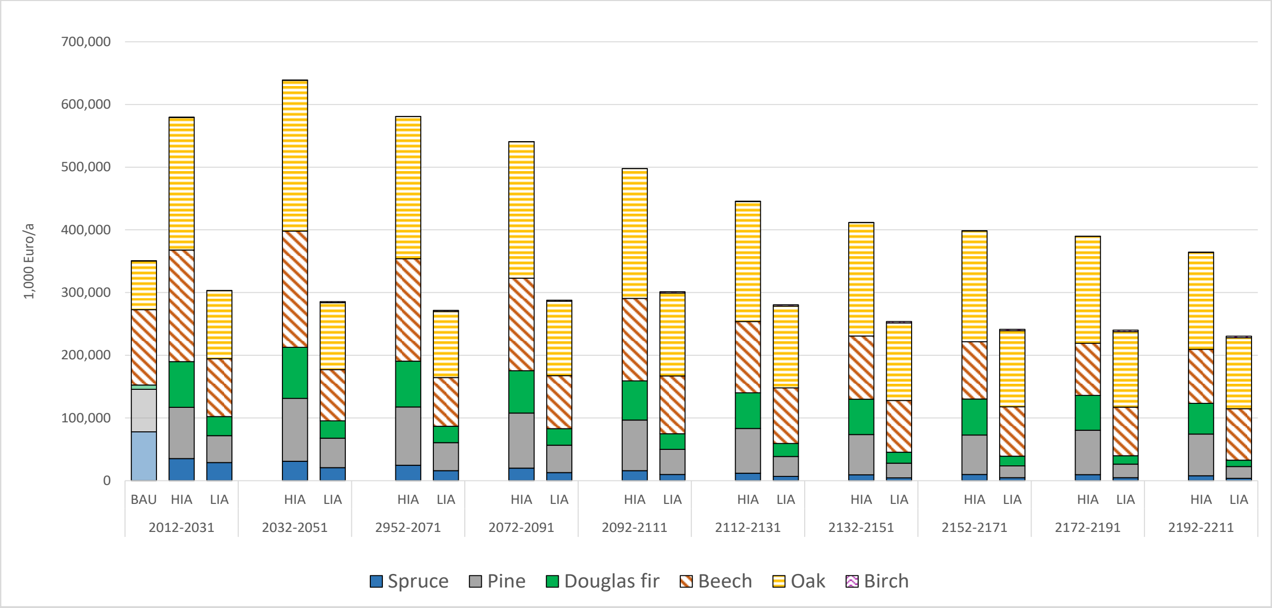
Figure 1: Tree species composition in 1,000 ha over the 200-year simulation period for the LIA- and HIA-scenario, with BAU depicted as a reference in the first period.



Source: own calculations

Figure 2 depicts the expenses for active forest adaptation measures to climate change by showing the costs for planting and pre-commercial thinning. In our HIA-scenario, the costs for forest conversion amount to 484 Mio. Euro/a on average over the simulation period, ranging from 364 Mio. Euro/a to 580 Mio. Euro/a. In the LIA-scenario, the costs for forest conversion amount to 269 Mio. Euro/a on average, ranging from 230 Mio. Euro/a to 303 Mio. Euro/a. Thus, the conversion costs in the LIA-scenario are about 44 % lower than in the HIA-scenario. When considering the LIA-scenario, it must be born in mind that the entire forest area with (potential) investment costs for planting and thinning is reduced over the entire simulation period, as the area share with birch (without these costs) increases continuously due to calamity. Analogously to the reduction of spruce and pine in the HIA-scenario, and the active conversion towards other species the investment costs in the HIA-scenario, especially in the first eighty years, greatly exceed the costs in the LIA-scenario in which calamity areas are largely left to low-cost succession. Compared to BAU, the costs for investments are twice as high in the first simulation period, whereas the investment costs in the LIA-scenario are of a comparable height.

Figure 2: Average annual investment costs for planting and thinning in 1,000 Euro/a over the 200-year simulation period for the LIA- and HIA-scenario, with BAU depicted as a reference in the first period

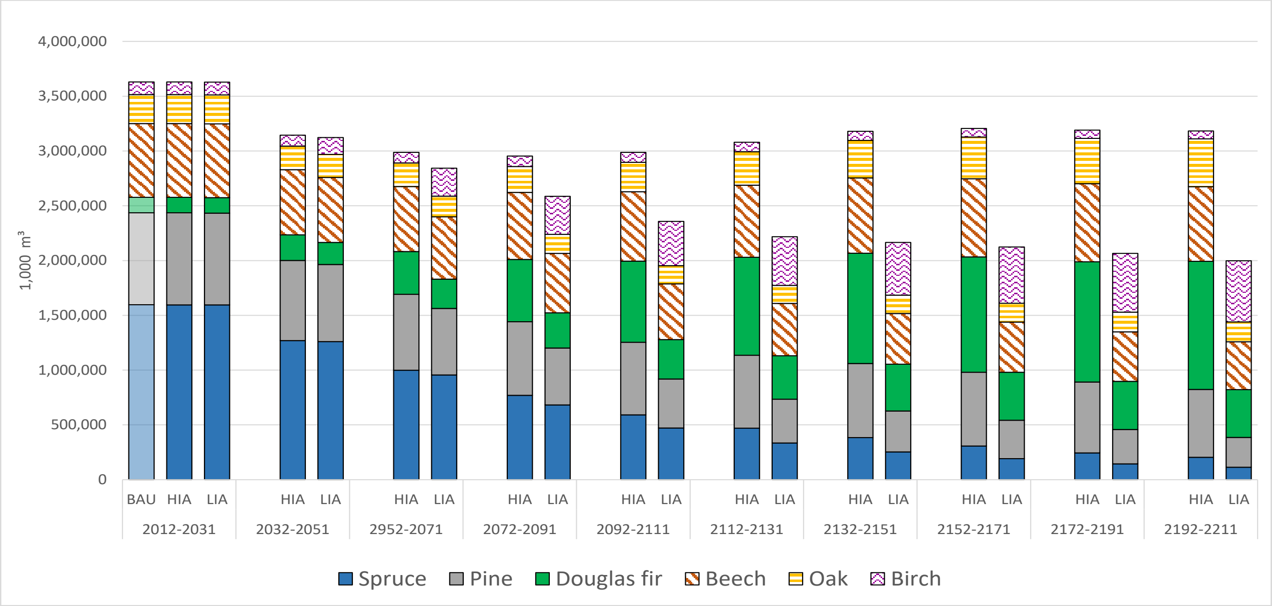


Source: own calculations

3.2 Growing stock and liquidation value

Figure 3 shows the different developments of growing stock in the LIA and HIA-scenario. As in the model all trees older than the maximum simulated stand age (production period plus 20 years) are felled at the beginning, the growing stock in all three settings shows a strong decline between the first and second 20-year period (“initial model effect”). In regard to the calamities in Germany in the years 2018-2020, this “model artefact” even actually corresponds well with reality and thus the model was not further improved in this regard. In the HIA-scenario, the total growing stock is reduced by 12 % in the long-term, mostly due to the reduction of spruce stock. In the LIA-scenario the total growing stock is reduced by 45 % over the simulation-runtime. Comparing the total growing stock of both scenarios, the HIA-scenario exceeds the LIA-scenario on average by 643 Mio m³ over bark (o.b.). While the growing stock declines in the both scenarios at first, the total growing stock in the HIA-scenario increases again after the third simulation period and largely remains constant for the rest of the time. In the LIA-scenario, on the other hand, although birch gains area from all tree species from calamity felling areas, its growing stock cannot compensate for the loss from other tree species groups and the growing stock keeps declining over the entire simulation.

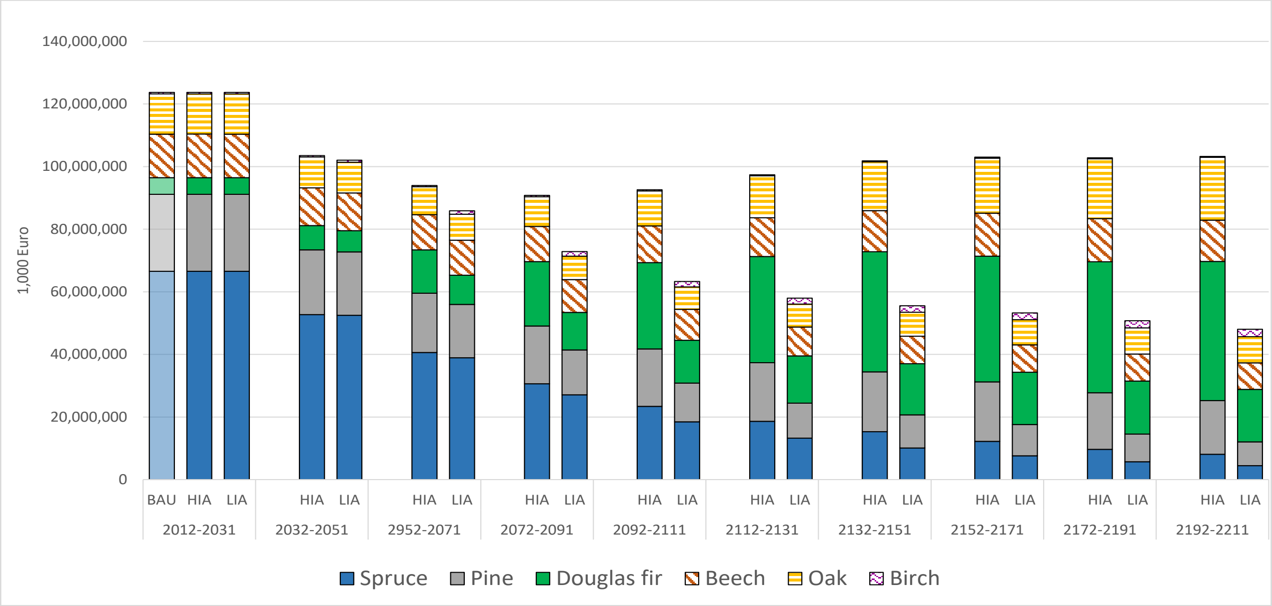
Figure 3: **Average annual growing stock in 1,000 m³ over bark over the 200-year simulation period for the LIA- and HIA-scenario, with BAU depicted as a reference in the first period**



Source: own calculations

Figure 4 shows the liquidation value as an average of each period in the scenarios. In the HIA-scenario the liquidation value over the 200-year simulation period is 101 bn Euro on average. A decrease of liquidation value is shown for the first four simulation periods, followed by a slight increase from the fifth period until the end of the simulation. The total decrease between the first and last period amounts to 17 %. In accordance to the development of the timber stock, the decrease of liquidation value is strongest in spruce with a decline of 46 % in relation to the total liquidation value. This is – partly – counteracted by an increase of liquidation value of Douglas fir, which amounts to 39 % in regard to the total liquidation value. The liquidation value of the LIA-scenario amounts to an average of 71 bn Euro over the simulation time, declining by 61 % between the first and last period. In this scenario the share of spruce decreases by 45 % and Douglas fir increases by 31 % in regard to the total liquidation value of all species. Since in the LIA-scenario there is no investment in high-yielding tree species on large areas, the liquidation value at the end of the simulation period is reduced to approximately half of the HIA-scenario.

Figure 4: **Average liquidation value per period in 1,000 Euro over the 200-year simulation period for the LIA- and HIA-scenario, with BAU depicted as a reference in the first period**



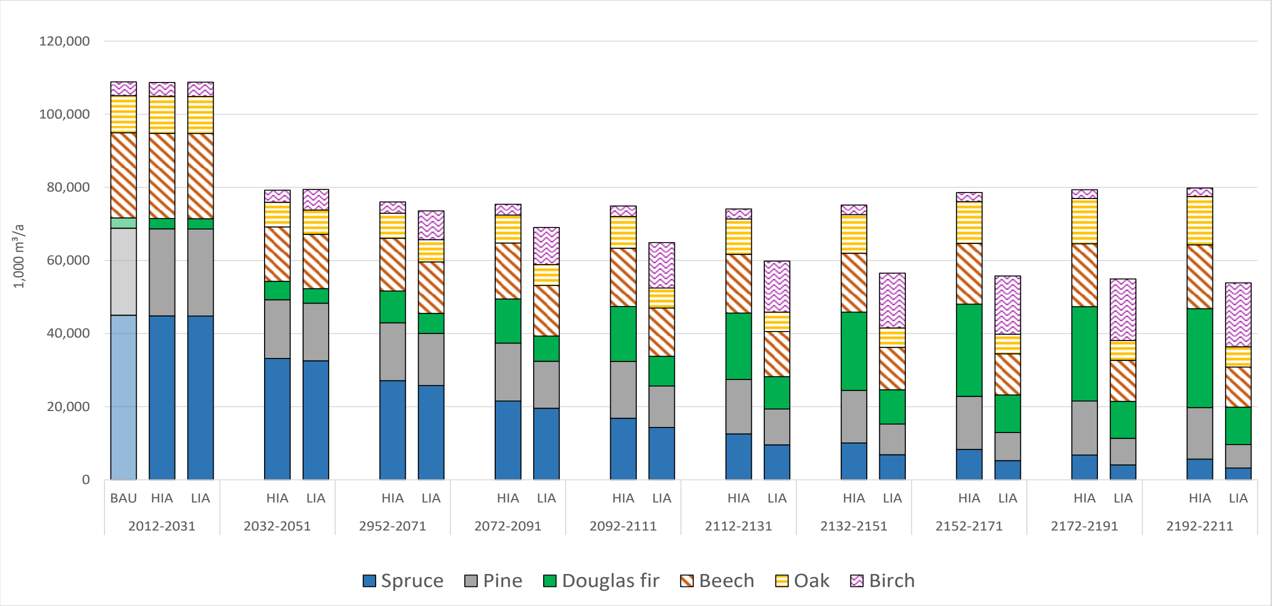
Source: own calculations

3.3 Felling amounts and silvicultural contribution margin

Figure 5 shows volume of harvested timber per year as an average of each period in the scenarios. The total harvested timber in the HIA-scenario show an average of 80 Mio m³ under bark (u.b.)/a over the simulation period. At first a decline of the total harvested timber due to the adaptations of forests to climate change and the increased loss of forest area to calamities becomes visible. Over the 200-year simulation period, the total fellings are reduced by 27 % between the first and last simulation period. The average harvested timber over all tree species in the LIA-scenario amounts to 68 Mio. m³ u.b./a over the 200-year simulation period and therefore, in comparison, to 84 % of the total amount of harvested timber in the HIA-scenario. The total amount of harvested timber is reduced by 50 % from the first to the last period in the LIA-scenario. Again, this is mainly due to the reduction of spruce, here by 35 % of the total amount of harvested timber over all tree species. Although birch largely increases in area and fellings, this cannot compensate the total loss of harvested timber amounts.

Regarding the results in Figure 5 starting from the second period, it becomes visible, that the average fellings in the HIA-scenario undergo only slight changes and remain constant at large. However, the harvested timber amounts are no longer dominated by spruce, but mainly by Douglas fir and to some degree by the deciduous species. The biggest reduction of timber fellings occurs in the LIA-scenario and the reduction continues over the entire simulation period. In this scenario, too, spruce is subject to heavy risk-related losses and is replaced by more climate change-adapted species and/or succession species.

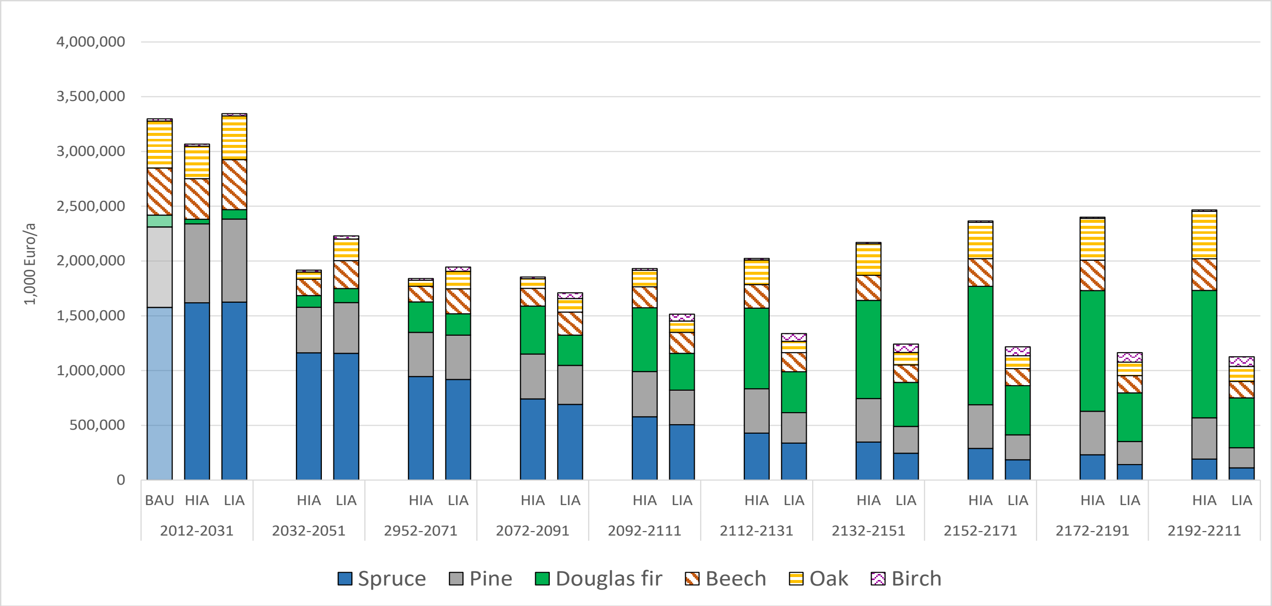
Figure 5: **Average amount of harvested timber in 1,000 m³ under bark per year over the 200-year simulation period for the LIA- and HIA-scenario, with BAU depicted as a reference in the first period**



Source: own calculations

Based on the volume of harvested timber, Figure 6 shows the SCM of the scenarios. In the HIA-scenario the SCM has an average of 2.2 bn Euro/a (207 Euro/ha/a over all tree species). As spruce is largely losing area and stock, the economic relevance also declines, which becomes visible in a reduction of its SCM by 45 % over all species. However, this loss is, under our model assumptions, compensated by the increase of the Douglas fir SCM by 46 % over all species. At the end of the simulation Douglas fir roughly reaches the SCM-level of spruce at the beginning of the simulation. In the LIA-scenario the average SCM over the entire simulation period and all tree species amounts to 1.7 bn Euro/a (158 Euro/ha/a) and is thus 24 % less than the average SCM in the HIA-scenario. The spruce-related SCM also shows the highest reduction and, with our model assumptions, other coniferous trees or birch do not compensate these financial losses. After a reduction of the SCM due to the initial model effect, at first a higher contribution margin can be reached than in the HIA-scenario, due to the lower planting and thinning costs. However, after about 60 years, this development is reversed. Towards the end of the simulation period the highest SCM can be reached in the HIA-scenario, clearly showing the advantage of climate change adapted forests. The difference between the SCM in the LIA- and HIA-scenarios over the 200-year simulation period is 0.5 bn Euro/a with a minimum of -0.3 bn Euro/a and maximum of 1.3 bn Euro/a.

Figure 6: **Average silvicultural contribution margin in 1,000 Euro/a over the 200-year simulation period for the LIA- and HIA-scenario, with BAU depicted as a reference in the first period**



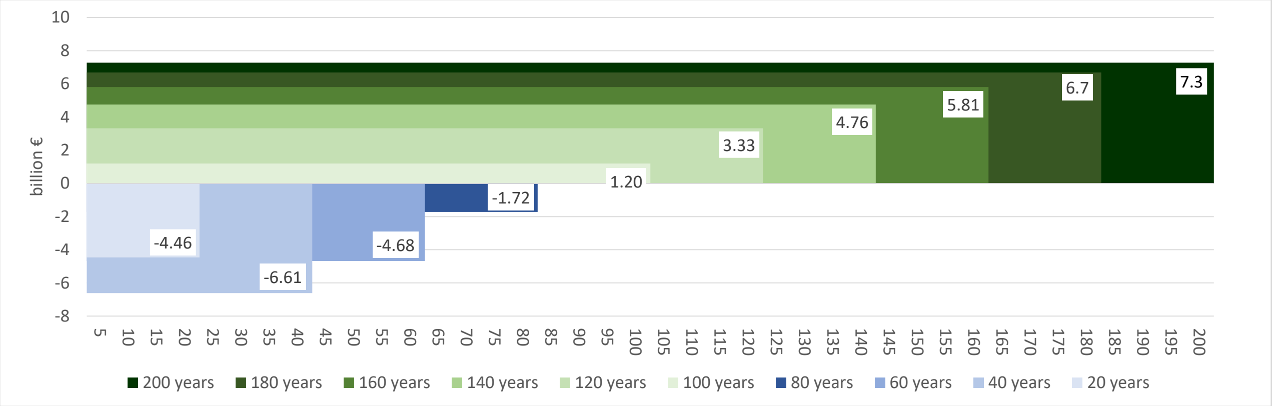
Source: own calculations

3.4 Impact of observation period on net present value

Figure 7 depicts the net present value differences of HIA- and LIA-scenario for different valuation periods, with HIA as minuend and LIA as subtrahend. In order to show the long-term economic impacts of the two scenarios we calculated the net present value as a sum of the average discounted contribution margins per 20-year period plus the discounted stand liquidation value at the respective last simulation period, choosing an interest rate of 1.5 %. The LIA-scenario is more advantageous than the HIA-scenario up to a valuation period of 90 years. Only after a valuation period of more than 90 years does the difference in net present value become positive and thus the HIA-scenario more advantageous from an economic point of view. This result reflects the initially high investment costs in active forest conversion for climate adaptation in the HIA, which are only offset by higher silvicultural profit margins and stand liquidation values towards the end of the 200-year simulation period.

This valuation is, however, heavily dependent on the selected interest rate. With increasing interest receivables, the advantages of the HIA-scenario shift to later valuation periods. From an interest rate of around 2.02 %, the HIA-scenario is never advantageous within the 200-year observation period in our example. At the same time, this result is an expression of the long-term nature and low return on equity of forestry production in Germany, under the present economic conditions. While in the HIA-scenario the current generations make a sacrifice in the form of high investment costs for active climate adaptation, the subsequent generations benefit. In the LIA-scenario, on the other hand, the current generations do not sacrifice on this scale. Due to the passive climate adaptation through omission of investment on the calamity areas, future generations would then have a forest with significantly reduced yield opportunities.

Figure 7: Net present value differences of HIA and LIA scenarios for different valuation periods in billion Euro



Source: own calculations

4 Discussion

4.1 Discussion of methods

In our study we aimed to assess the long-term economic impacts of active climate change adaptation strategies compared to passive, successional adaptation strategies on the forestry sector in Germany. Our simulation-model, the FESIM, proved to be a suitable basic model that could be adapted and enhanced in order to fit our research needs. It depicts external framework conditions as well as internal management decisions and shows, in result, a simplified representation of reality, enabling us to appraise long-term impacts of current developments and different management strategies on the forestry sector in Germany. The model goes beyond short-term forest growth simulations on single tree or stand level. It is nevertheless a complex model, unifying a multitude of factors, such as growth and assortment functions, climate change influenced survival probabilities, changed tree species compositions and others, which can complicate the interpretation of results. In order to keep scenario-complexity to a minimum and to simplify interpretation between the HIA- and the LIA-scenario, we used equal basic assumptions and varied only the future tree species composition, based on latest scientific findings. By changing only this aspect, we follow the assertion of Möhring and Dieter (2020:101), that a "model should enable progress in knowledge, it should still be transparent due to its simplicity, and due to its similarity to the real system it should contribute to the understanding of the complex, in this case, forest economic reality".

For the six tree species included in FESIM, we incorporated climate-sensitive changes in survival probabilities into the model. These figures, based on Brandl et al. (2020), include the survival probabilities of older stands but not losses of plantings due to, *e.g.*, drought. For compensation, we increased cultivation costs to include expenses for additional plantings. Additionally, we included factors for calamity-induced shortfalls in revenue and additional expenses for calamity-timber harvesting. Changes in forest growth, that could result in increased or reduced mass outputs as a result of changed precipitation or longer vegetation periods (Pretzsch et al., 2014), on the other hand, were hitherto not implied in the model. We therefore assumed, that the future growth of site-suitable tree species is similar to their growths on previous sites, even under climate change conditions.

Furthermore, it should be emphasized that the model employs calculations based on idealized monocultures. Mixed stands, that would enhance stability of forests in extreme weather events, cannot be modelled directly. Consequently, on parts of the German forest area survival probabilities could be better than actually depicted in our research. Also, we did not consider a reduction of the production cycle as a response to climate change induced risks. In order to improve our results, forest growth simulators based on single trees might have been used. Yet, simulations of this kind are usually conducted for a maximum of 40 years. As we aimed to give an overview of long-term average economic impacts of adaptation strategies for German forests and not the exact conditions on single stand level, we deemed our assumptions and calculations as viable and suitable for the purpose. Also, the extent to which individual enterprises and regions are adversely affected by climate change in Germany can vary considerably. For reasons of model simplicity, we calculated with mean values for all of Germany and not with distributions. A regionalization of the model would also be beneficial in order to show which regions in Germany will be particularly affected by climate change and the necessary forest restructuring and mitigation strategies.

For the economic data base, we used average timber revenues and felling costs from the German FADN from the pre-calamity years 2013 – 2017. As the model does not yet allow for dynamic price calculations, the costs and revenues remain fixed over the 200-year simulation period, as do the factors for unprocessed timber from calamities, calamity-induced shortfalls in revenue and additional expenses of harvesting. Further, choosing to focus on the impact of the strategies on timber fellings and timber revenues, (changes in) administration costs were not included. On the one hand, as timber demands and prices change due to market conditions and increases in administrational costs due to climate crisis management can be expected, this can be regarded as serious shortcoming of the calculation. On the other hand, hardly any predictions over the change of prices and revenues can be made over such a long period. Also, reliable data in changes of administrational costs were not available at the time of calculation. As a further worthwhile supplement, future research could focus on incorporating price-elasticities or Monte-Carlo-Simulations into the model in order to account for increases and decreases in prices in the aftermath of calamities and subsequent lagged shortages in timber supply.

4.2 Discussion of results

In general, the FESIM results show a climate change induced shift in tree species composition with less coniferous and more deciduous trees, a diminished standing timber stock in volume and value, less felling amounts, and respectively a reduction of contribution margin. The yield opportunities in raw wood production deteriorates as a result of climate change for German forestry compared to the current business-as-usual of forest management. Even active forest conversion, as depicted in the HIA-scenario, although mitigating the development, does not counteract this trend completely.

In regard to economic viability, the HIA-scenario renders a lower SCM as compared to the LIA-scenario in the beginning, due to higher investment costs for planting site adapted species. Yet, this relation changes in the 60 years after the start of the simulation. Whereas the SCM of the HIA-scenario, starting from the second period, continuously increases during the simulation runtime, the SCM of the LIA-scenario decreases steadily and accounts for only about half of the SCM in the HIA-scenario at the end of the simulation. The increase of SCM in the HIA-scenario is mainly driven by fast-growing, coniferous species, here represented by Douglas fir. However, the HIA-scenario assumes that German forest enterprises are financially able to invest in forest climate change adaptation on a large scale. In this scenario, for the next 50 years investments in a range of 540 and 640 Mio. Euro would have to be made annually in climate-adapted forest conversion over the next century. Over the 200-year simulation period, the investment on average would be 485 Mio. Euro. Even under very good economic conditions, the German forestry industry was able to generate an annual entrepreneurial income of 1.4 bn. Euro in the years 2008 – 2017 according to the German Economic Accounts for Forestry (Rosenkranz, 2019). With an increase in calamity events and the medium-term disappearance of spruce, it therefore seems very questionable that these high investment costs in climate-adapted forest conversion can be refinanced through raw wood production alone.

Against the background of capital shortage and the entrenchment of capital over an extended duration in forestry, an important driver for the dynamic analysis is the choice of the interest rate. In our study we chose to use the interest rate of 1.5 %, introduced by Möhring (2001), which is widely recognized in German forestry. With this relatively low interest rate, the net present value of the HIA-scenario only exceeds that of the LIA-scenario after more than 90 years. But with a higher interest rate (here: about 2.02 %), an investment in active climate change adaptation would no longer be advantageous compared to the LIA-scenario.

The extensive renunciation of active reforestation of the current calamity forest areas in Germany is also often demanded by nature conservationists, who consider natural forest development by succession an essential contribution to biodiversity protection. As the LIA-scenario shows, this development would lead to a notable reduction of the domestic timber supply. Dieter et al. (2020) estimated the effects of the decrease of felling in the EU for the implementation of the EU Biodiversity Strategy (European Commission, 2020b). They found out, that around three quarters of the decrease in felling in the EU is compensated for by additional felling in third countries. Positive impacts on EU biodiversity due to the additional protection could thus also be offset by negative impacts in non-EU countries. In this regard it is questionable, which adaption reactions and leakage effects will follow the decrease of domestic timber supply as given in the LIA-scenario.

As a whole, the total growing stock, in the LIA-scenario is always lower than in the HIA-scenario. Therefore, it becomes clear, that the demand for high growing stocks in order to retain carbon in forests while at the same time setting aside large forest areas for nature conservation (*e.g.* as a result of the implementation of the EU-Biodiversity Strategy), cannot be met under the conditions of our model assumptions. So, from the point of view of the forest climate contribution, there is more to be gained by striving for high intensity forest management with active forest conversion. However, this statement only applies to the standing wood stock as one compartment of the carbon store in the forest. The consideration of other storage compartments, such as *e.g.* deadwood stock or soils, can lead to different results.

To examine our model results for plausibility, we could not find any studies that were suitable to compare our results with and due to the complexity of the model no sensitivity analysis is available. Naturally, the model settings and assumptions have a big influence on model results. In our study we strove for using the most current and scientifically verified input data in order to depict reality as best as possible, while at the same time aiming to produce results that are easy to understand and interpret. Therefore, we chose to only change the settings for tree species change and investment costs in the two scenarios, which leads to these being the most influential factors of our central results, while all other input data remains constant. However, these assumptions can lead to over- and underestimations of model results, which will be discussed in the following paragraphs.

Regarding the development of timber stock and felling amounts in our study, an overall reduction in both scenarios, compared to the beginning of the simulation, becomes visible. This strong reduction, especially in spruce and pine, is a consequence of the increasing risk and decreasing survival probability with increasing stand age (Brandl et al., 2020). In the model, we chose to use average rotation periods from WEHAM 2012 (BMEL, 2016), *e.g.* 120 years for spruce. We are aware that these rotation periods are not economically adapted, however, as we deem the rotation period not only the expression of an optimized timber production but also of other ecosystem services, like *e.g.* carbon storage, we chose to not change the rotation periods in the course of the simulation runtime. In reality though, forest enterprises would most likely strongly reduce the rotation period in order to adapt timber production to rising default risks. As we did not account for a risk-reduction by adapting the rotation periods we overestimate the economic loss.

Through a climate-change induced reduction of domestic timber supply, and an anticipated equal or subsequent intensifying demand, timber prices from regular and calamity fellings are expected to increase. In this case, the degree of processing of calamity timber is expected to increase. Consequently, our assumption of a processing degree of 80 % of calamity timber may become outdated. Such a development would lead to an overestimation of the economic loss in our study.

A further overestimation of the economic loss could be deduced from innovation in hardwood processing, that might be developed in response to a higher share of supply of deciduous trees in the future, that would in turn increase demand and, subsequently, prices. As price changes or fluctuations cannot be depicted in the FESIM to-date, our economic model results might therefore overestimate the negative economic impacts of climate change on German forestry.

In our study we also imply, that successional areas stocked would be stocked with low-yield successional species for the duration of the simulation runtime and that high-yield climax tree species would not grow again without active planting. In reality, natural regeneration could also lead to a change in tree species towards more climate-resistant and higher-yielding climax species, leading to an overestimation of the negative impacts in our study.

The investment costs for active forest adaptation are of great importance for the scenario results. The costs of regeneration after regular felling and after calamity were estimated on current regeneration methods under the current climatic conditions. In climate change, it can be assumed that regeneration will be exposed to additional abiotic and biotic risk factors, particularly due to extreme weather events. Changes of the survival probabilities for young trees are not included by Brandl et al. (2020). In principle, it is more likely that the regeneration costs will be higher as a result of climate change, *e.g.* through necessary irrigation or frequent failure of plantings (Gömann et al. 2015)) and therefore the economic effects could be underestimated in our study.

Our assumptions on calamity-induced shortfalls in revenue are based on the calamity events in the years 2018-2020 in Germany (Möhring et al., 2021). They can result from timber quality-reductions and additionally from market disruptions. Since there were significant market disruptions for spruce in 2018 – 2020, the shortfalls in revenue on spruce and Douglas fir are comparatively high in our study. Opposed to this, studies, *e.g.* by Prestemon and Holmes, 2010; Möllmann and Möhring, 2017, use lower quality-related shortfalls for calamity timber. Therefore, with our simulation settings, there could be an overestimation of the damage in spruce and Douglas fir. However, due to the level and frequency of calamities in our scenarios, it seems more likely that calamities would also lead to market disruptions of other tree species, with the result that our own results would underestimate the overall level of damage.

5 Conclusion

With our study we aimed to contribute to the current discussion of climate change adaptation in (German) forestry. Inactivity after forest disturbance as a strategy in forest management to adapt to climate change leads to decreasing timber stocks, felling amounts and, in consequence, to a deterioration of the income and financial status of German Forestry. In contrast, active forest conversion with a high level of investment costs and at a low-level of interest rates impairs economic results in the short and medium term but is economically advantageous in the long-term. Active forest adaptation to climate change requires the willingness of current generations for large investments over many decades. While future generations would benefit from these investments through better opportunities to use wood, current generations would have to make major sacrifices.

Although we cannot exclude uncertainties of long-term modelling, such as changes of site and climatic characteristics as well as societal demands and market dynamics, the FESIM-model shows a target-oriented and efficient production planning with a detailed and dynamic view of costs and income for the long-term and could be developed for further research.

High uncertainty on future climate and forest growth conditions could deter forest owners from spending the required amounts of money for adaptation measures in their forests. Financial support in the adaptation process will be crucial to balance the burdens and costs of necessary adjustments. Multiple societal benefits of resilient and productive forests could justify a cost-sharing approach between forest owners and society.

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Appendix A – Model input data

Appendix Table 1: BAU-scenario: Tree species composition after regular final felling and after calamities (%)

		Original tree species					
		Spruce	**Pine**	**Douglas fir**	**Beech**	**Oak**	**Birch**
Share of tree species after rejuvenation (%)	**Spruce**	84	3	6	4	2	9
	Pine	2	89	3	2	3	8
	Douglas fir	1	1	84	0	1	0
	Beech	7	3	1	87	10	7
	Oak	2	2	2	4	82	5
	Birch	4	2	3	3	3	70

Source: NFI 2002, NFI 2012

Appendix Table 2: **HIA- and LIA-scenario: Tree species composition after regular final felling and after calamities (%)**

			Original tree species					
			Spruce	**Pine**	**Douglas fir**	**Beech**	**Oak**	**Birch**
Share of tree species after rejuvenation (%)	**Tree species area share after regular final felling**							
	High intensity adaptation and Low Intensity adaptation	Spruce	40	0	0	0	0	0
		Pine	10	75	0	10	0	0
		Douglas fir	20	5	100	10	0	0
		Beech	20	10	0	70	0	10
		Oak	10	10	0	10	100	10
		Birch	0	0	0	0	0	80
	Tree species area share after calamity in %							
	High intensity adaptation	Spruce	40	0	0	0	0	0
		Pine	10	75	0	10	0	0
		Douglas fir	20	5	100	10	0	0
		Beech	20	10	0	70	0	0
		Oak	10	10	0	10	100	0
		Birch	0	0	0	0	0	100
	Tree species area after calamity in %							
	Low intensity adaptation	Spruce	20	0	0	0	0	0
		Pine	0	20	0	0	0	0
		Douglas fir	0	0	20	0	0	0
		Beech	0	0	0	20	0	0
		Oak	0	0	0	0	20	0
		Birch	80	80	80	80	80	100

Source: own assumptions based on Spellmann (2020)

Appendix B – Model results

Appendix Table 3: Tree species composition in 1,000 ha over the 200-year simulation period for the LIA- and HIA-scenario and differences between the scenarios

	Year	2012 - 2031	2032 - 2051	2952 - 2071	2072 - 2091	2092 - 2111	2112 - 2131	2132 - 2151	2152 - 2171	2172 - 2191	2192 - 2211
High Intensity Adaptation	Spruce	2,663	2,112	1,677	1,320	1,034	819	654	536	464	403
	Pine	2,741	2,727	2,697	2,657	2,612	2,568	2,525	2,472	2,425	2,402
	Douglas fir	347	605	823	1,016	1,184	1,326	1,445	1,549	1,639	1,713
	Beech	2,516	2,654	2,750	2,814	2,848	2,857	2,849	2,827	2,774	2,725
	Oak	1,237	1,463	1,660	1,843	2,012	2,163	2,297	2,422	2,539	2,634
	Birch	1,123	1,066	1,019	978	936	895	857	820	785	752
Low Intensity Adaptation	Spruce	2,613	1,955	1,452	1,058	760	552	407	313	256	211
	Pine	2,632	2,349	2,083	1,844	1,638	1,466	1,321	1,186	1,064	964
	Douglas fir	277	366	435	496	546	580	596	600	594	579
	Beech	2,415	2,310	2,202	2,107	2,032	1,967	1,908	1,855	1,802	1,770
	Oak	1,133	1,095	1,053	1,028	1,025	1,030	1,028	1,025	1,021	1,012
	Birch	1,557	2,552	3,402	4,095	4,626	5,034	5,366	5,650	5,890	6,092
Differences	Spruce	50	157	225	262	274	267	247	224	208	192
	Pine	109	379	614	813	974	1,102	1,204	1,286	1,361	1,438
	Douglas fir	70	239	388	520	638	746	849	949	1,045	1,134
	Beech	101	344	548	707	817	890	941	972	973	955
	Oak	104	368	607	815	987	1,134	1,269	1,398	1,518	1,622
	Birch	-435	-1,487	-2,383	-3,117	-3,690	-4,138	-4,509	-4,829	-5,105	-5,340

Source: own calculation

Appendix Table 4: **Average annual investment costs for planting and thinning in 1,000 Euro/a over the 200-year simulation period for the LIA- and HIA-scenario and differences between the scenarios**

	Year	2012 - 2031	2032 - 2051	2952 - 2071	2072 - 2091	2092 - 2111	2112 - 2131	2132 - 2151	2152 - 2171	2172 - 2191	2192 - 2211
High Intensity Adaptation	Spruce	35,373	30,967	24,485	20,045	15,866	11,896	9,234	9,751	9,569	7,895
	Pine	81,711	100,161	93,104	87,909	80,945	71,307	64,237	63,166	70,821	66,551
	Douglas fir	72,807	81,477	72,995	67,561	62,244	57,017	56,410	57,255	55,621	48,935
	Beech	177,985	185,548	163,231	147,390	131,738	113,694	100,923	91,427	82,997	86,085
	Oak	211,483	240,486	226,763	217,580	206,751	191,400	180,660	176,751	170,719	154,684
	Birch	320	480	408	369	357	351	334	317	304	292
Low Intensity Adaptation	Spruce	28,828	20,724	15,954	12,948	9,952	6,782	4,594	4,832	4,769	3,776
	Pine	43,045	46,905	44,794	43,730	39,966	31,758	23,169	18,827	21,526	18,747
	Douglas fir	30,339	27,871	26,089	26,257	25,055	20,879	17,609	15,268	13,622	10,092
	Beech	92,263	81,630	77,547	84,624	92,065	88,558	82,654	78,839	77,393	82,225
	Oak	108,510	106,724	105,512	118,490	132,186	130,412	123,545	121,273	120,333	113,052
	Birch	320	1,795	1,743	1,800	1,988	2,179	2,278	2,357	2,447	2,521
Differences	Spruce	6,545	10,243	8,531	7,097	5,914	5,113	4,641	4,919	4,800	4,119
	Pine	38,666	53,256	48,310	44,179	40,979	39,549	41,068	44,339	49,295	47,804
	Douglas fir	42,468	53,606	46,907	41,304	37,190	36,138	38,801	41,986	41,999	38,843
	Beech	85,723	103,918	85,683	62,766	39,673	25,136	18,269	12,589	5,605	3,860
	Oak	102,973	133,761	121,251	99,090	74,565	60,988	57,115	55,478	50,387	41,632
	Birch	0	-1,315	-1,335	-1,432	-1,631	-1,828	-1,944	-2,040	-2,143	-2,230

Source: own calculation

Appendix Table 5: Average growing stock in 1,000 m³ over bark over the 200-year simulation period for the LIA- and HIA-scenario and differences between the scenarios

	Year	2012 - 2031	2032-2051	2952-2071	2072-2091	2092-2111	2112-2131	2132-2151	2152-2171	2172-2191	2192-2211
High Intensity Adaptation	Spruce	1,594,695	1,269,587	999,230	769,781	591,344	469,859	383,663	306,517	244,663	204,375
	Pine	840,548	731,736	691,879	672,086	662,704	665,916	677,268	674,238	645,786	619,685
	Douglas fir	141,438	232,631	391,319	568,312	740,319	894,964	1,005,260	1,052,816	1,098,141	1,169,221
	Beech	673,568	595,461	592,628	612,095	633,558	657,684	687,782	712,997	712,636	680,493
	Oak	264,100	214,688	215,343	236,682	268,506	304,981	342,873	380,392	413,612	436,158
	Birch	115,401	99,862	97,061	95,386	91,155	86,338	82,714	79,471	76,036	72,677
Low Intensity Adaptation	Spruce	1,594,459	1,259,340	954,932	682,584	471,466	335,479	253,273	191,497	144,735	113,027
	Pine	838,830	705,218	607,844	519,587	447,027	398,638	373,504	350,480	312,526	272,830
	Douglas fir	140,738	200,172	267,049	320,783	360,539	396,849	428,012	437,598	440,390	435,980
	Beech	673,563	593,730	569,763	542,345	507,645	477,543	462,419	458,075	451,397	436,953
	Oak	264,080	210,642	188,546	173,846	165,917	164,217	167,418	173,474	179,140	180,560
	Birch	117,164	152,925	254,211	346,838	405,169	444,604	480,800	512,125	536,975	557,860
Differences	Spruce	236	10,247	44,298	87,197	119,878	134,380	130,390	115,020	99,928	91,349
	Pine	1,718	26,518	84,036	152,498	215,678	267,277	303,764	323,758	333,260	346,855
	Douglas fir	700	32,459	124,270	247,529	379,779	498,114	577,248	615,218	657,751	733,241
	Beech	5	1,731	22,864	69,750	125,913	180,141	225,363	254,921	261,239	243,540
	Oak	20	4,046	26,797	62,836	102,589	140,763	175,455	206,918	234,472	255,597
	Birch	-1,763	-53,064	-157,150	-251,452	-314,014	-358,266	-398,086	-432,654	-460,940	-485,183

Source: own calculation

Appendix Table 6: **Average liquidation value per period in 1,000 Euro over the 200-year simulation period for the LIA- and HIA-scenario and differences between the scenarios**

	Year	2012-2031	2032-2051	2952-2071	2072-2091	2092-2111	2112-2131	2132-2151	2152-2171	2172-2191	2192-2211
High Intensity Adaptation	Spruce	66,559,627	52,737,982	40,582,732	30,644,707	23,379,825	18,648,878	15,295,806	12,202,948	9,663,436	8,077,046
	Pine	24,568,842	20,649,303	18,984,060	18,418,776	18,392,590	18,714,569	19,127,901	18,991,145	18,066,157	17,182,010
	Douglas fir	5,345,508	7,779,889	13,815,881	20,573,256	27,536,486	33,919,710	38,386,999	40,208,686	41,846,194	44,415,501
	Beech	13,905,143	12,008,829	11,223,296	11,216,610	11,713,703	12,369,674	13,096,064	13,706,344	13,805,345	13,192,522
	Oak	12,822,545	9,898,897	8,960,278	9,542,685	11,205,600	13,376,023	15,592,750	17,581,339	19,125,648	20,077,960
	Birch	491,422	425,250	413,324	406,192	388,171	367,660	352,229	338,417	323,789	309,486
Low Intensity Adaptation	Spruce	66,560,311	52,494,699	38,946,112	27,093,898	18,485,124	13,263,198	10,111,472	7,635,631	5,710,344	4,453,030
	Pine	24,565,025	20,244,958	17,019,736	14,348,327	12,363,153	11,162,188	10,589,071	9,983,888	8,863,670	7,628,284
	Douglas fir	5,345,667	6,787,838	9,347,574	11,965,260	13,671,605	15,102,743	16,315,172	16,712,950	16,915,602	16,768,554
	Beech	13,905,232	12,022,231	11,148,043	10,509,445	9,863,061	9,222,033	8,822,626	8,715,639	8,650,732	8,421,119
	Oak	12,822,864	9,863,263	8,310,604	7,461,079	7,199,060	7,321,837	7,646,968	8,036,303	8,336,354	8,408,805
	Birch	498,931	651,215	1,082,529	1,476,971	1,725,364	1,893,297	2,047,433	2,180,824	2,286,649	2,375,583
Differences	Spruce	-683	243,283	1,636,620	3,550,809	4,894,701	5,385,680	5,184,334	4,567,317	3,953,091	3,624,017
	Pine	3,817	404,345	1,964,324	4,070,449	6,029,438	7,552,381	8,538,830	9,007,256	9,202,487	9,553,726
	Douglas fir	-159	992,051	4,468,307	8,607,996	13,864,881	18,816,967	22,071,826	23,495,736	24,930,591	27,646,948
	Beech	-89	-13,402	75,253	707,165	1,850,642	3,147,641	4,273,438	4,990,705	5,154,613	4,771,403
	Oak	-319	35,634	649,674	2,081,606	4,006,540	6,054,186	7,945,782	9,545,036	10,789,294	11,669,155
	Birch	-7,509	-225,965	-669,206	-1,070,779	-1,337,193	-1,525,636	-1,695,204	-1,842,407	-1,962,860	-2,066,097

Source: own calculation

Appendix Table 7: **Average amount of harvested timber in 1,000 m³ under bark per year over the 200-year simulation period for the LIA- and HIA-scenario and differences between the scenarios**

	Year	2012-2031	2032-2051	2952-2071	2072-2091	2092-2111	2112-2131	2132-2151	2152-2171	2172-2191	2192-2211
High Intensity Adaptation	Spruce	44,851	33,223	27,127	21,549	16,841	12,573	10,055	8,317	6,788	5,650
	Pine	23,810	16,056	15,847	15,872	15,560	14,895	14,417	14,530	14,767	14,088
	Douglas fir	2,835	5,027	8,687	12,047	15,034	18,135	21,405	25,216	25,812	27,077
	Beech	23,275	14,864	14,432	15,310	15,926	16,083	16,096	16,631	17,222	17,476
	Oak	10,182	6,754	6,866	7,650	8,674	9,670	10,599	11,414	12,369	13,241
	Birch	3,767	3,333	3,090	2,945	2,869	2,749	2,614	2,501	2,400	2,297
Low Intensity Adaptation	Spruce	44,816	32,550	25,793	19,577	14,309	9,583	6,885	5,227	4,075	3,223
	Pine	23,806	15,784	14,244	12,837	11,363	9,775	8,391	7,710	7,287	6,410
	Douglas fir	2,830	3,963	5,481	6,919	8,130	8,860	9,378	10,269	10,105	10,245
	Beech	23,275	14,853	14,087	13,830	13,204	12,341	11,572	11,299	11,221	10,982
	Oak	10,181	6,659	6,109	5,715	5,475	5,339	5,330	5,328	5,454	5,542
	Birch	3,866	5,657	7,859	10,171	12,431	13,957	15,009	15,958	16,802	17,488
Differences	Spruce	34	674	1,334	1,972	2,532	2,990	3,171	3,089	2,713	2,427
	Pine	4	273	1,603	3,035	4,197	5,120	6,026	6,820	7,480	7,678
	Douglas fir	5	1,064	3,206	5,128	6,905	9,275	12,027	14,946	15,707	16,832
	Beech	0	10	345	1,480	2,722	3,742	4,524	5,332	6,001	6,493
	Oak	1	95	758	1,935	3,199	4,331	5,270	6,086	6,914	7,699
	Birch	-99	-2,324	-4,769	-7,226	-9,562	-11,208	-12,395	-13,457	-14,403	-15,191

Source: own calculation

Appendix Table 8: **Average silvicultural contribution margin in 1,000 Euro/a over the 200-year simulation period for the LIA- and HIA-scenario and differences between the scenarios**

	Year	2012-2031	2032-2051	2952-2071	2072-2091	2092-2111	2112-2131	2132-2151	2152-2171	2172-2191	2192-2211
High Intensity Adaptation	Spruce	1,617,926	1,161,453	945,785	741,610	578,326	428,974	347,996	289,661	231,147	191,242
	Pine	720,459	416,340	402,924	409,395	411,721	404,404	397,020	398,929	396,902	378,078
	Douglas fir	42,716	107,222	277,233	437,936	583,091	736,612	895,205	1,080,609	1,101,172	1,162,960
	Beech	371,305	148,763	142,658	161,734	190,638	214,840	228,877	252,566	279,308	287,471
	Oak	295,977	65,279	54,918	88,081	152,114	224,823	287,015	331,040	379,987	433,914
	Birch	19,377	16,948	15,735	15,007	14,627	14,013	13,320	12,748	12,232	11,708
Low Intensity Adaptation	Spruce	1,624,338	1,157,535	919,130	691,021	505,690	337,223	245,796	185,913	141,926	111,844
	Pine	759,129	462,911	403,733	356,796	316,007	277,842	244,857	227,082	209,889	183,141
	Douglas fir	85,226	129,133	195,700	275,141	336,116	373,725	401,524	449,634	443,767	456,160
	Beech	457,031	252,808	227,708	210,790	191,430	174,995	159,881	155,635	157,315	149,747
	Oak	398,962	198,484	159,084	123,839	103,055	103,602	113,589	117,244	124,866	136,494
	Birch	19,885	27,789	39,253	51,230	62,893	70,703	76,091	80,968	85,295	88,805
Differences	Spruce	-6,411	3,917	26,655	50,589	72,636	91,751	102,200	103,748	89,221	79,399
	Pine	-38,670	-46,571	-809	52,599	95,714	126,562	152,163	171,847	187,014	194,937
	Douglas fir	-42,509	-21,911	81,533	162,795	246,974	362,887	493,681	630,976	657,405	706,801
	Beech	-85,726	-104,045	-85,051	-49,056	-792	39,846	68,996	96,932	121,992	137,724
	Oak	-102,985	-133,205	-104,166	-35,758	49,059	121,221	173,426	213,796	255,120	297,421
	Birch	-509	-10,841	-23,519	-36,223	-48,265	-56,690	-62,771	-68,221	-73,063	-77,097

Source: own calculation

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