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Aiming at a moving target: economic evaluation of adaptation strategies under the uncertainty of climate change and CO_2 fertilization of European beech (*Fagus sylvatica* L.) and Silver fir (*Abies alba* Mill.)

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Abstract

Key message Drought severely worsened till 2100 and eventually outplayed growth-enhancing CO_2 fertilization turning productivity gains into losses for beech and fir. Most scenarios generated notable losses in profitability but economic tipping points were later than for productivity due to lag effects related to discounting. Time mixture of fir and shortening rotation can counteract economic risks under climate change, but requires early admixture and moderate establishment costs.

Context Adaptation strategies to climate change (CC) such as establishing mixed forests are often based on ecological understanding while economic rationale is often disregarded.

Aims This paper studies CC uncertainty on productivity and profitability of European beech (*Fagus sylvatica* L.) and Silver fir (*Abies alba* Mill.). Besides, the economic consequences to actively adapt beech forests by admixing Silver fir are investigated.

Methods We used the process-based forest growth model GOTILWA + to simulate RCP2.6, RCP4.5 and RCP8.5 climatic projection by the MPI-ESM-LR global circulation model (MPI-ESM-LR) with the CO_2 fertilization effect (eCO_2) switched on and off. We analysed the sensitivity of the land expectation value (LEV) on CC and economic parameters.

Results CC initially increased productivity, but declined after a tipping point (2040–2070) and later also profitability (2045–2100). RCP8.5 had positive, RCP2.6 negative and RCP4.5 neutral effects on LEV. Switching off eCO_2 turned RCP8.5 from the most profitable to the least profitable scenario and the opposite for RCP2.6. CC generally reduced optimal rotation (R_{opt}) being scenario dependant, but comparatively more for fir than beech. Admixing fir created an economic benefit when implemented before stand age 50 of beech. This benefit was nullified with protection costs for browsing control (fencing or tree shelters).

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

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Conclusions Economic parameters (not CC) were the major source of uncertainty stemming from discounting factors and establishment costs. Admixture of fir and shortening rotation can provide a solution to tackle economic and climate uncertainties, but requires early admixture and browsing control.

Keywords Climate change adaptation, eCO_2, Drought, Mixed forests, Land expectation value, Uncertainty

1 Introduction

The extreme summer drought of 2018 and dry conditions in the follow-up years have provided drastic evidence of climate change impacts in Germany, and also other central European countries (FOREST EUROPE 2020; Schuldt et al. 2020). Spruce and pine plantations are facing a forest decline due to a combination of drought, windthrow and bark beetle calamities. More than 245 million m^3 of damaged timber accumulated between 2018 and 2022 in Germany (as of 30.06.2022) with periodic price drops up to 24% (Popkin 2021; Destatis 2022). More than 450,000 ha have to be reforested in the coming decades (Popkin 2021; BMEL 2022a). Unprecedented funding schemes have been implemented by federal and state authorities to deal with the consequences adding up to 800 million € (BMEL 2022a). Yet, the total estimated costs of 12.7 billion € in the period 2018 to 2020 alone exceed by far the provided funding schemes (Möhring et al. 2021). This development is dramatic because three quarters of the annual timber harvest in Germany come from fast-growing conifers—the backbone of the wood industry in Germany (Destatis 2022).

Forest authorities and decision-makers are thus facing great uncertainties and challenges to find solutions for future forest systems and to make species choices that are ecologically stable while maintaining forest goods and services. Adaptation strategies to climate change are, however, mainly based on ecological reasoning and less so on the economic feasibility or socio-economic demands (but see Knoke et al. 2005, Friedrich et al. 2019; Paul et al. 2019). The investment costs of conversion to mixed forest may not pay off depending on the profitability of the admixed tree species. Besides, conversion creates insecurity on how to handle transition and management of the newly established forest systems. For this, the study by Brunette et al. (2020) gave an important insight demonstrating that private forest owners perceive investment in adaptation strategies often as more risky for their business than climate change impacts themselves. It is thus of pivotal importance for climate change adaptation to improve the understanding of the uncertainty in the decision making process because uncertainty may inhibit behavioural change (Moure et al. 2023). This calls for a more holistic approach supporting forest practitioners with robust strategies to establish ecologically stable, but also economically beneficial forests (Radke et al. 2017, 2020). Achieving sustainable forest management in this area of conflict of demands in ecology, socio-economy and economy while facing perceptible changes in the climate is increasingly resembling aiming at a moving target.

European beech (*Fagus sylvatica* L.) has been in the centre of large-scale transformation strategies as it naturally dominates the forest landscape in most parts of central Europe (Ellenberg 1996; Willner et al. 2017). After being largely replaced by Norway spruce (*Picea abies* L.) and Scots pine (*Pinus sylvetris* L.) monocultures in the nineteenth and twentieth century (Spiecker 2003), beech is now seeing a revival with steadily increasing shares in public forests in the past decades (BWI 2012). The trend will be fortified in the future as beech dominates the natural regeneration with 30% in Germany (BWI 2012; BMEL 2016). Successful at first glance, the competitive nature of beech will require efforts for an active conversion if the objective is to achieve mixed, multi-functional and ecologically stable forests (Ellenberg 1996; Barna and Bosela 2015).

Silver fir (*Abies alba* Mill.) has been more recently suggested as future target species to adapt central European forests to climate change (e.g. Bosela et al. 2018). Considering the increase of broadleaves and the decline of spruce and pine, the timber industry will be in great demand for softwood in the coming decades (Schier et al. 2018). Its taproot system reduces the risk of windthrow and makes it more drought resilient (Zang et al. 2014; Vitali et al. 2017; Schwarz and Bauhus 2019; Magh et al. 2020). Fir is a prime candidate to be co-cultivated with beech especially in mountain ecosystems (Schwarz and Bauhus 2019) where it often naturally occurs in mixtures with beech (Oberdorfer 1977; Otto 1994; Ellenberg 1996; Willner et al. 2017). Potential benefits in productivity are related to higher above- and belowground resource-use efficiency through complementarity effects and competition reduction (Zhang et al. 2012).

While dendroecological approaches can only look into the past growth performance, the future of these two species under climate change is highly uncertain. Drought susceptibility of beech is a debated question (Geßler et al. 2007; Valladares 2008; Bolte et al. 2009; Tegel et al. 2014; Metz et al. 2016). Silver fir generally benefits from a warmer climate, but drought years especially in combination with secondary agents (bark beetles) can lead to increased mortality (Büntgen et al. 2014), as also recently witnessed in the Black Forest (FVA-BW 2019, 2020) or in the Vosges mountains with 60% of salvage cuttings from regular harvesting plans after drought in 2019 (ONF 2019a, b). Three factors of uncertainty are temperature, precipitation and elevated atmospheric CO_2 concentration (eCO_2)—and their interplay. Different levels of eCO_2 can act as fertilizer for plant growth—termed the *CO_2 fertilization effect* (Norby et al. 2005). CO_2 fertilization, temperature rise and extended growing season accelerated forest productivity in Europe in the past century (Spiecker 1999; Kahle et al. 2008; Pretzsch et al. 2014; Bravo-Oviedo et al. 2014). Recent evidence shows that the CO2-fertilization is responsible for an increase of 13.5 ± 3.5% or 15.9 ± 2.9 PgC (mean ± s.d.) between 1981 and 2020 (Keenan et al. 2023) - which represents a huge impact of anthropogenic emissions on the worldwide ecosystems. Increasing events of heat spells combined with extended drought periods can, however, reduce productivity (Ciais et al. 2005) and increase mortality (Allen et al. 2010, 2015). The observed productivity gains in central Europe may turn into losses in the near future (Reyer et al. 2017; Sperlich et al. 2020). This will strongly depend on latitude and altitude—for instance mountain and boreal forests are mainly energy- and not water limited (ALRahahleh et al. 2018; Kellomäki et al. 2018; Sedmáková et al. 2019; Liang et al. 2019). If growth conditions worsen beyond the environmental envelope of tree species, shifts in species distribution and occurrence can occur (Anderegg et al. 2013) as for beech in the southernmost distribution range (Jump and Penuelas 2005; Jump et al. 2006) leading to geographic changes in the cultivation of tree species.

Climate change impacts and responses of forest ecosystems that are relevant for economic consideration are summarized in Fig. 1. Large-scale disturbances decrease the standing stock, reduce quality and timber value enforced by price drops due to oversupply leading to unprofitable salvage operations. Future climate conditions may decrease productivity leading to longer production times, lower harvesting volumes, lower revenues and the opposite. Whereas southern and central Europe will likely suffer from northward tree migration of less productive and less valuable tree species, higher altitudes and latitudes may likely benefit (Hanewinkel et al. 2013).

In this model-simulation study, we aim to provide a holistic approach examining the growth performance of beech and fir under future drought of climate change with the detailed process-based forest growth simulator GOTILWA + while addressing ecological and economic uncertainties for forest managers. Specifically, we address the CO_2 fertilization effect which has not yet been evaluated economically. We investigate whether profitable forest management with beech and fir can be maintained in a potential drought-risky area in lower altitudes of the sub-mountainous belt of the Black Forest under future climatic changes. We also examine the economic benefit of fir admixture as potential adaptation scenario for beech forests. More specifically,

(A) We assess the relative contribution of drought and eCO_2 on growth and productivity of beech and fir until the end of the century.
(B) We test whether profitable forest management with beech and fir is still possible under climate change using the land expectation
(C) We analyse the tipping points where increasing drought offsets positive eCO_2 effects in productivity and also profitability
(D) We quantify the uncertainty of ecological and economic factors in our scenarios
(E) We examine whether admixing fir into beech forests generates an economic benefit under climate

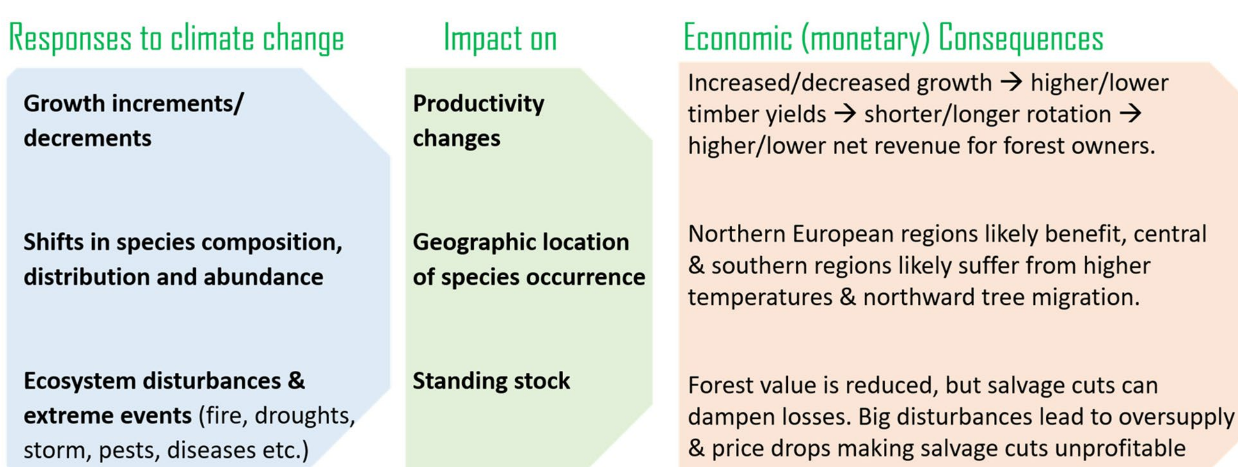

Fig. 1 Summary of potential responses of forest ecosystems to climate change and their potential economic impacts focusing on consequences on monetary values (not considering non-monetary values/services)

change taking into account timing of admixture as well as scenarios of varying establishment costs.

For this approach, detailed mechanistic process-based forest growth models are needed which dispose of a management module for forestry applications (Keenan et al. 2011; Hickler et al. 2015; Sperlich et al. 2020) and which are then coupled with economic models as management decisions cannot be based alone on climate change impacts on forest productivity (Knoke and Seifert 2008; Paul et al. 2019; Radke et al. 2020). Species distribution models are often used to project the environmental suitability and probability of species occurrence under future climates (Hanewinkel et al. 2014; Dyderski et al. 2018; Baumbach et al. 2019). They are, however, rather static and blend out the feedback of growth processes with the climate as well as compensatory effects by eCO_2 fertilization (Keenan et al. 2011; Hickler et al. 2015). Process-based models such as GOTILWA + describe mechanistically the ecophysiology of forests under drought (Gracia et al. 1999; Keenan et al. 2009; Nadal-Sala et al. 2019a; Sperlich et al. 2020) and will thus provide a more solid projection of future species performance.

Our paper will underpin management decisions under climate change uncertainty with an ecological but also economic rationale. This interdisciplinary task will provide a formal framework as a basis for meaningful policy recommendations widening the debate with the economic perspective.

2 Material and methods

2.1 *The biogeochemical forest growth model GOTILWA +*

GOTILWA + (Growth Of Trees Is Limited by WAter, http://www.creaf.uab.es/gotilwa/) is a detailed process-based biogeochemical model that simulates tree growth, and the associated carbon and water fluxes to investigate effects of tree stand structure, management interventions, soil properties, water stress and climate change (Gracia et al. 1999; Keenan et al. 2009; Nadal-Sala et al. 2019a; Sperlich et al. 2020). GOTILWA + has been validated against different data sets and has been shown to perform well under different climate zones, e.g. in boreal, temperate and Mediterranean climate regions for evergreen broadleaved and conifers and deciduous species (Kramer et al. 2002; Morales et al. 2005; Keenan et al. 2009; Nadal-Sala et al. 2017, 2019b; Bugmann et al. 2019). The advantage of process-based models is that they represent mechanistically the relationship of growth processes with the environment. Once the growth processes are validated, they can be parametrized and calibrated also in other regions for simulation experiments where potentially no validation data exists.

We parametrized and calibrated GOTILWA + within a large interdisciplinary project with on-site ecophysiological field data from experimental sites near Freiamt in the Black Forest (Germany) at 440 m a.s.l. (48° 08.863′ North 7° 54.331′ East) dominated by beech (61%) and silver fir (32%), others (7%) and a nearby meteorological station for the climate data (< 5 km) (BuTaKli 2019). For more details, see our companion paper Sperlich et al. (2020). The management regime was established with *forest development types* defined for Baden-Württemberg (LFBW 2014) and local silvicultural handbooks (Klädtke and Abetz 2010) calibrated with local increment and yield tables for beech and fir for Baden-Württemberg (see Fig. 2 in Sperlich et al 2020 Climate). In this paper, we transformed the simulation output of Sperlich et al., (2020) into merchantable assortments and monetized the output for our economic analyses.

The calibrated model thus simulates beech and fir forests in the sub-mountainous zone under business-as-usual management regimes of public forests in Baden-Württemberg under current and future climate projections. We chose the simulation start in the year 2000 to be able to reflect the juvenile development phase of beech. Many forest managers are or will be facing a similar problem due to the high share of beech (30%) in the natural regeneration in Germany (BWI 2012; BMEL 2016). In this development phase, forest managers are still able to adapt easier the forest stands before big investments are at risk by silvicultural changes. The study area is considered to be a drought-risk area for beech and fir regarding increasing drought impacts under future climate change being located at a rather low-altitude, sub-mountainous zone of the Black Forest.

In GOTILWA +, climate change is represented by a change in temperature and precipitation and also CO_2. It thus allows to simulate the CO_2 fertilization effect by elevated atmospheric CO_2 (eCO_2) and its positive feedback on forest growth. The model does not include other biotic/abiotic disturbances or extreme events (storm, fire, insect pests and diseases, etc.) besides drought and simulates monospecific forests. We used the climatic projection by the MPI-ESM-LR global circulation model from the Max Planck Institute taken from the WorldClim database (http://www.worldclim.org/) with three representative concentration pathways (RCP2.6, RCP4.5 and RCP8.5). The respective decadal mean annual temperature increments were 1.8, 2.6 and 4.4 °C; annual CO_2 increments were 0.21, 1.38 and 5.36 ppm; and total annual precipitation decrements were 25, 24 and 27 mm (9. Table 3). The climate data for the reference scenario with business-as-usual management assuming no climate change (noCC) was generated with the built-in weather generator of GOTILWA + based on a climate time series

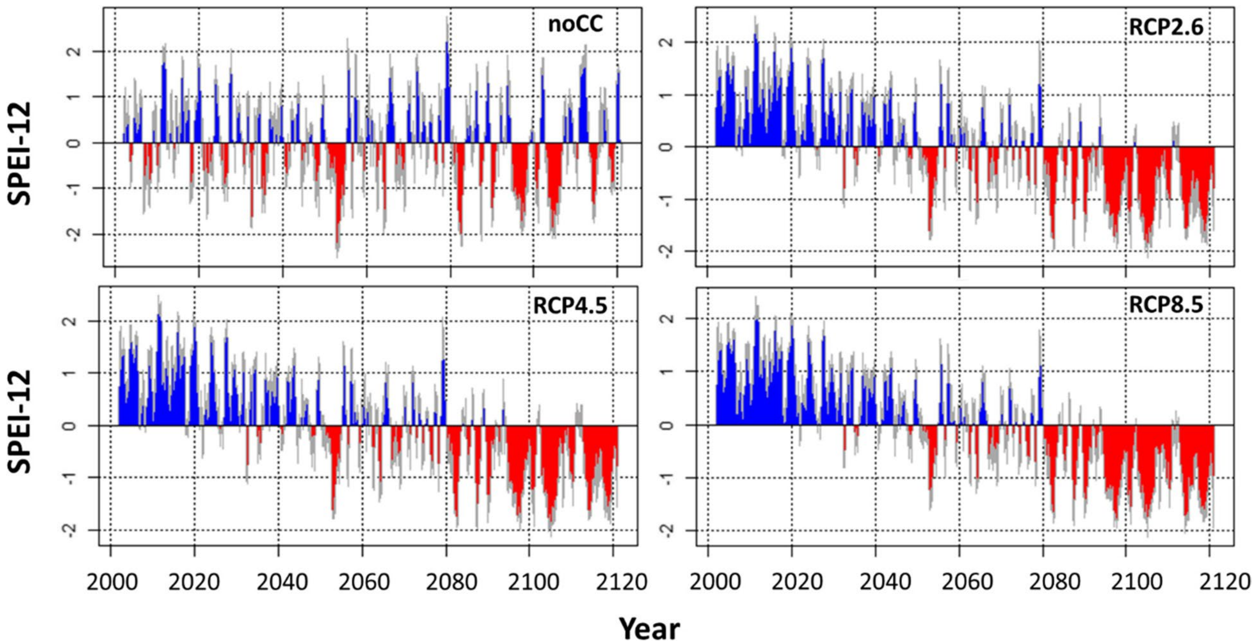

Fig. 2 Monthly Standardized Precipitation Evapotranspiration Index (SPEI) of the climate scenarios no climate change (noCC), RCP2.6, RCP4.5 and RCP8.5. Positive values indicate that the difference between monthly precipitation and potential evapotranspiration is larger than the average for a given monthly period. Negative values thus represent conditions drier than average. The monthly periods used were 3, 6, 12 and 24 months for SPEI-3, SPEI-6, SPEI-6 and SPEI-24, respectively

(1973–2017) from a nearby meteorological station. More details can be found in our companion paper Sperlich et al. (2020). RCP2.6, RCP8.5 and RCP4.5 represent the optimistic, pessimistic and medium climate scenario regarding the human mitigation measures against climate change (IPCC 2013). The three RCP scenarios were additionally run with constant atmospheric CO_2 concentration at 370 ppm in order to investigate the extent of the "CO_2 fertilization" (eCO_2) which is the positive feedback of increased atmospheric CO_2 concentration on vegetation growth. For this study, we considered six climate change scenarios: three RCPs with eCO_2 switched on and off. Additionally, we investigated the potential acclimation to higher CO_2 levels while keeping side effects of eCO_2, e.g. improved water use efficiency. The additional simulation runs of the three RCPs with eCO_2 switched on but with photosynthetic downregulation is covered in Sperlich et al. (2020) and was not the focus of this paper.

We used the multi-scalar, monthly standardized precipitation evapotranspiration index (SPEI) (Vicente-Serrano et al. 2010) to analyse the climate data from Freiamt and to compare the created climate data sets of the different climate scenarios no climate change (noCC), RCP2.6, RCP4.5 and RCP8.5 (R-package "SPEI" version1.7). SPEI is a multiscalar drought index. It incorporates temperature and precipitation and can be used for determining the onset, duration and magnitude of drought conditions with respect to normal, average condition. It is thus a very useful indicator of future drought but also temperature stress under various future scenarios.

2.2 Classification and monetarisation of the simulation output

The stem volume of each DBH- class was classified for 11 assortments using the software BDATPro (Kublin and Bösch 2007). The output was then monetised with the species-specific, regional wood prices and harvesting costs (Table 1 and 9. Fig 10) and finally integrated to the whole stand at every management intervention (5-year interval). Wood prices and harvesting costs are classified in 9 diameter classes of roundwood, industrial wood and fuel wood, respectively for beech and fir (Table 1). Values were averaged for the period 2000 to 2016 for Baden-Württemberg over all wood quality classes and were inflation-corrected. In this period, variances in timber prices are priced in (a) high prices for beech roundwood due to a period peak of demands in Asia (2000–2005) and low prices thereafter (2006–2016); (b) low timber prices for fir due to oversupply of softwood after a major storm event in 1999 (2000–2006) and high prices after the recovery of prices (2007–2016) (Table 1 and 9. Fig 11). Therefore, we conducted a sensitivity analysis considering periods of high and low timber prices for beech and for fir (Table 1 and 9. Figs. 11 and 12).

Table 1 Timber prices and harvesting costs (€/m^3) of 9 diameter classes of roundwood, industrial wood (Ind. wood) and fuel wood for beech and fir for the period 2000 to 2016 for Baden-Württemberg (inflation corrected). Prices represent mean prices achieved for all wood quality classes (A, B, C) during this period. Mean values are additionally displayed for periods of high prices (for beech 2000–2005 and for fir 2007–2016) and low prices (for beech 2006–2016 and for fir 2000–2006)

	Roundwood diameter classes									Ind. wood	Fuel wood	
	10–15	15–20	20–25	25–30	30–35	35–40	40–45	50–55	60 +			
Beech	21.6	33.8	36.2	44.6	57.2	66.8	76.5	94.4	104.9	38.6	20.0	Price
	16.36	21.86	24.83	40.60	54.68	72.99	86.59	120.42	140.72	26.58	10.80	High Price (2000–2005)
	24.45	38.85	42.36	46.80	58.56	63.46	70.92	80.17	85.34	45.20	37.35	Low Price (2006–2016)
	26.0	25.0	22.0	21.0	19.0	18.0	16.0	18.0	18.0	26.0	0.0	Harvesting Costs
Fir	38.6	60.2	68.2	73.7	74.0	72.8	71.1	67.2	68.0	31.6	10.0	Price
	27.51	44.06	54.01	59.18	59.70	58.76	58.35	56.86	61.50	26.42	27.63	High Price (2000–2006)
	46.31	71.48	78.09	83.94	84.03	82.63	80.02	74.48	72.48	35.21	45.99	Low Price (2007–2016)
	21.0	21.0	20.0	19.0	18.0	17.0	16.0	17.0	17.0	21.0	0.0	Harvesting Costs

For validating the created diameter distribution in the model, we compared the modelled stands with monetized inventory plots near our study site using the same price and cost table. The inventory plots were selected for covering a wide range of age classes (9. Fig. 13).

2.3 Economic evaluation of simulation output forest profitability

We applied the land expectation value of the standard Faustmann approach (Faustmann 1849) to calculate the optimal timepoint for final harvesting—the optimal rotation age (R_{opt})—considering the standing timber as capital and forestry operations as investment expressed as a series of discounted cash flows with interest rate (i) issued from managed forestland. The LEV is the sum of all NPV's over an infinite number of rotation cycles aiming at finding the maximum LEV at R_{opt} calculated as:

$$LEV = \frac{\sum_{t=1}^{R} (v_t - c_t) * q^{R-t}}{q^R - 1} \quad (1)$$

where v_t is the harvesting and stumpage revenue at time t, c_t are the costs to harvest the timber at time t, q represents the discounting factor $(1+i/100)$, and R is the rotation time. We concentrated on decision relevant costs for the different scenarios applied and therefore ignored administration costs for simplicity. We used $i=2\%$ representing the potential average earning of secure government bonds in Germany (Dieter 2001; Hanewinkel et al. 2010; Neuner et al. 2015). Rotation age is considered optimal when LEV reaches its maximum at constant i ($LEV_{max,i=2}$). In an additional sensitivity analyses, we studied the effect of $i=1$, 3, 4 and 5% on LEV and R_{opt}.

We used the LEV to be able to quantify the impacts of drought and eCO_2 on economic productivity meaning the maximum LEV and R_{opt}, but also to be able to identify tipping points when the economic productivity in CC scenarios fell below our reference scenario.

We also calculated the internal rate of return (IRR). IRR is the discount rate at which the benefits of the LEV (or NPV) equal the costs and at which the investment reaches net zero. Forest business often use the IRR to evaluate the economic performance of forest investments or forest projects.

2.4 Adapting beech forests to climate change by admixing silver fir

We used the net present value (NPV) approach for the economic assessment of the adaptation strategy because beech is commonly managed with longer rotation ages than fir. This precludes the application of the LEV which requires equally long, infinitely repeating rotation cycles. Positive payments are summed minus the present value of negative payments made at different points in time divided by the discounting factor (Klemperer 1996), as follows:

$$NPV = \frac{\sum_{t=1}^{R} (v_t - c_t)}{q^R} \quad (2)$$

We tested a potential adaptation strategy for young beech forests by admixing Silver fir with three admixing ratios 85:15, 70:30 and 55:45 (percent of species share). As GOTILWA + does only allow to simulate monospecific forests, we have used the simulation output and recalculated the mixed forest stands posterior ignoring potential complementarity or competition effects.

The aim of the fir admixture was to create an added value at the end of the rotation of beech (120 years). The tree density of admixed fir was 240, 480 and 720, respectively (1600 trees per ha). To account for the fact that beech was the desired target species, the highest share of admixed fir was 45% with 55% of beech. Fir is one of the most heavily browsed tree species in central Europe requiring careful protection of fir regeneration (Vitasse et al. 2019). Timepoint of admixture, planting costs and regeneration protection are major elements in the cost plan. We analysed the costs of three admixing scenarios. In one scenario, we assumed deer management with a cost-neutral, strict hunting policy to reduce browsing pressure. In two other scenarios, we included the costs of fencing or single tree protection with tree shelter tubes as a response to excessive browsing. Planting density was 1600 tree per ha with costs of 2128 € per ha (0.35 € per plant for planting plus 0.98 € per plant for 25–50 cm saplings). Fencing costs were 2000 € per ha (5€ per m) for a low-priced game fence. Alternatively, cost for tree shelter tubes were 4432 € per ha (2.77 € per plant), with decomposable material (no deconstruction costs) with a longevity until saplings' heights exceed critical age. Costs were estimated using quotes from regional entrepreneurs. Aiming at beech as dominant species, we assumed species shares of 85:15, 70:15 and 55:45. No planting costs were accounted for beech as it mostly originates from cost-neutral, natural regeneration. Costs for fir were recalculated for respective species share. We used the NPV to evaluate the fir admixture because the diverging production cycles of beech and fir admixture precluded the application of LEV.

2.5 Scenario uncertainty and the contribution of climate change and economic assumptions

We analysed whether climate change represented by changes in temperature, precipitation and atmospheric elevated CO_2 (eCO_2) introduced more uncertainty in the results of LEV_{max} than the economic assumptions represented by different discounting factors and by establishment and protection costs. The climate change uncertainty included the effect of six scenarios (RCP2.6, RCP4.5 and RCP8.5 with eCO_2 switched on and off). The economic uncertainty included the application of five discounting factors (0.01 to 0.05) and changes in timber prices (see "2.2" and Table 1). For fir, two additional scenarios were included addressing establishment costs: planting and protection (fencing/tree shelters).

3 Results

3.1 Impact of climate change on productivity

The drought index SPEI shows that the past 18 years in the study region have already become drier than average (Fig. 3). This trend worsened notably for the three applied RCP scenarios. The drought conditions were comparable for RCP2.6 and RCP4.5. In RCP8.5, however, SPEI was notably lower with more severe drought conditions.

For displaying the impact of climate change and increased drought, we used the current annual increment (CAI) (m^3 per ha and year) as productivity measure—and not net primary productivity (NPP) as used in ecology—because CAI represents the commercial timber volume. All scenarios showed notable growth reductions compared to noCC. However, CAI increased in the initial simulation period and turned into losses after a certain tipping point (Fig. 2, Table 2). The initial productivity gains were highest for RCP8.5 and lowest for RCP2.6. The tipping points were at simulation year 2070 for RCP8.5, and 2040 for RCP4.5 and RCP2.6 for both beech and fir (Table 2). When the CO_2 fertilization effect was switched off (eCO_2), productivity gains (up to the tipping point) were low and the losses after the tipping notably higher. RCP8.5 turned from the most productive to the least productive scenario (Fig. 2b).

When eCO_2 was switched off, the tipping points were between 2040 and 2050 for all scenarios for both beech and fir. De-activating the CO_2 fertilization effect with photosynthetic downregulation (PD) but keeping eCO_2 switched on compensated some productivity losses due to improved water-use efficiency especially in RCP8.5, but only marginally in RCP4.5 and RCP2.6 (9. Fig. 14).

The total accumulated growth (TAG) sums the CAI, the harvested volume and deadwood volume over the entire observation period and serves as accumulated measure for forest productivity. In RCP8.5, TAG accumulated 1356 m^3 per ha for beech and 2362 m^3 per ha for fir at the end of simulation period (stand age 120), which was 15 and 19% higher compared to noCC, respectively (9. Fig. 15). In RCP2.6 and RCP4.5, TAG of beech were higher than noCC until 2050 and 2080 for beech and 2050 and 2070 for fir (respectively) and, unlike RCP8.5, fell thereafter below the TAG in noCC. At the end of the simulation period, TAG was 24 and 21% lower in RCP2.6 for beech and 11 and 8% lower in RCP4.5 for fir (respectively). Standing timber volume (SV) of beech and fir were higher in the RCP scenarios and then dropped below noCC in 2055 and 2045 for RCP 2.6 and in 2070 and 2060 for RCP 4.5, respectively. (9. Fig. 16). In RCP 8.5, the SV of both species did not fall below noCC, but peaked at 499 and 526 m^3 per ha in 2060 (respectively) and then equalled the value in noCC towards the end of the simulation period. Compared to CAI, the tipping points of SV were later and the losses less pronounced. Growth enhancement due to eCO_2 accumulated and persisted longer in standing timber volume (compared to CAI) and also resulted in a higher harvesting volume (HV) for beech until 2060 in RCP 2.6 and 4.6 and in RCP 8.5 until 2100 (9. Figs. 16 and 18). The tree numbers in the CC scenarios were identical than in noCC (harvesting

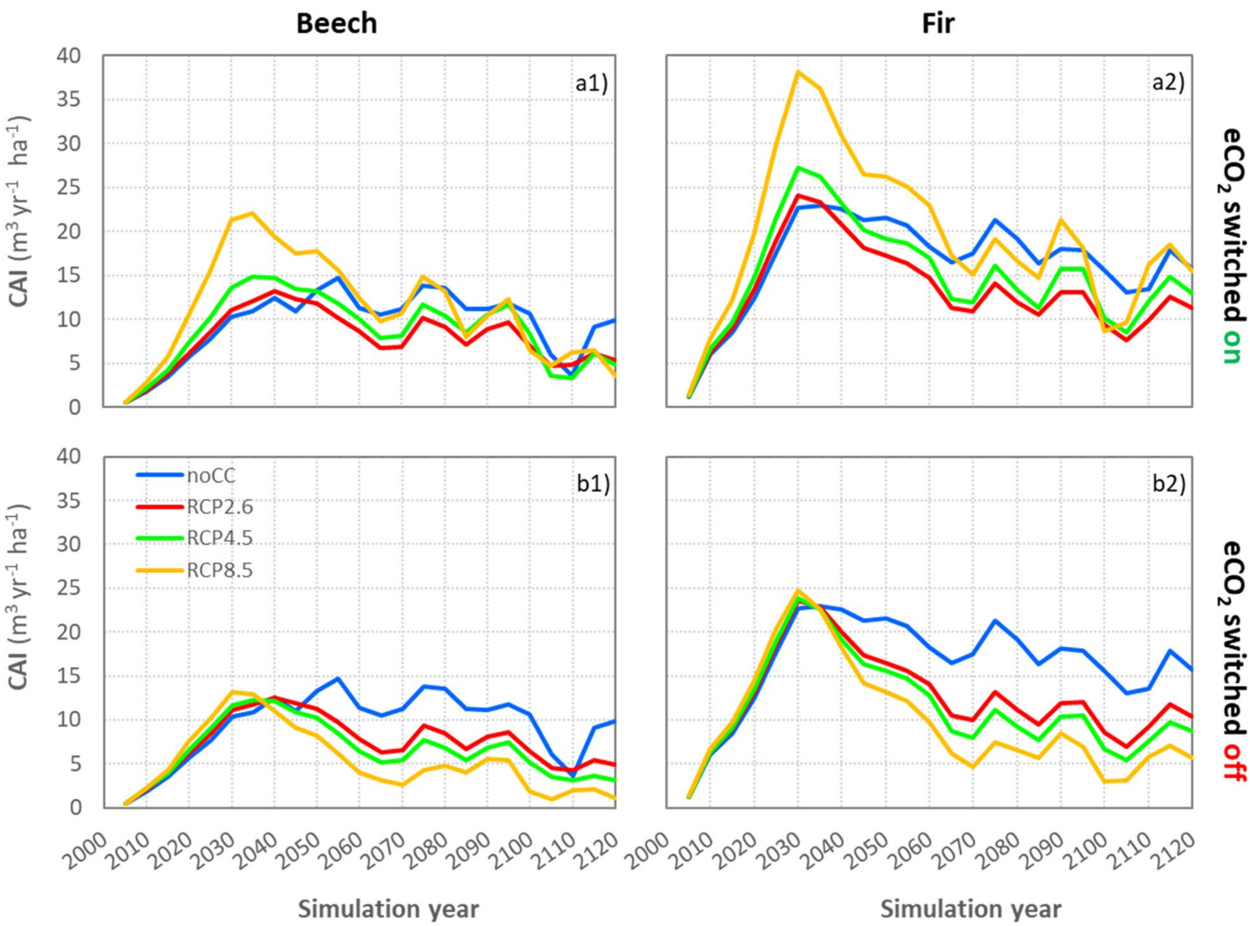

Fig. 3 Effect of three climate change (CC) scenarios (RCP2.6, RCP4.5, RCP8.5) on current annual increment (CAI) of beech (1) and fir (2) with eCO2 switched on (**a**), eCO2 switched off (**b**). The reference scenario noCC is displayed for comparison. Data basis was the simulation output from Sperlich et al (2020)

Table 2 Tipping points of productivity (current annual increment—CAI) and economy (land expectation value—LEV) for beech and fir. Tipping point represent the year when the value of productivity or economy in the climate change (CC) scenarios fall below our reference scenario no climate change (noCC). Six climate change scenarios (RCP2.6, RCP4.5, RCP8.5 with eCO_2 switched on and off, respectively) were considered. Empty cells indicate when noCC was not underrun and no tipping point was detected

		Beech		Fir	
eCO_2	CC scenario	CAI	LEV	CAI	LEV
On	RCP2.6	2050	2055	2040	2045
On	RCP4.5	2050	2100	2045	2075
On	RCP8.5	2065	-	2070	-
Off	RCP2.6	2055	2035	2045	2055
Off	RCP4.5	2055	2035	2045	2055
Off	RCP8.5	2055	2035	2045	2055

mode: tree number) to keep the same tree density and to identify the effect of CC without interference potentially introduced by other harvesting modes (e.g. volume, basal area).

3.2 Impact of climate change on the land expectation value of beech and fir

Our scenarios for beech and fir started on bare land assuming successful stand establishment via natural regeneration. In our reference scenario assuming no climate change (noCC), the LEV (2%) was 1.6 times higher for fir (11.947 € per ha) compared to beech (7.456 € per ha) (Fig. 4). Optimal rotation was at stand age 75 for fir and 100 for beech (simulation year 2075 and 2100, respectively). These two noCC scenarios were our baseline scenarios to analyse climate change impacts on LEV.

Effects of the RCP- scenarios on the LEV with eCO_2 switched on ranged from positive to negative (independent of the species) (Fig. 4). The peak of LEV was in

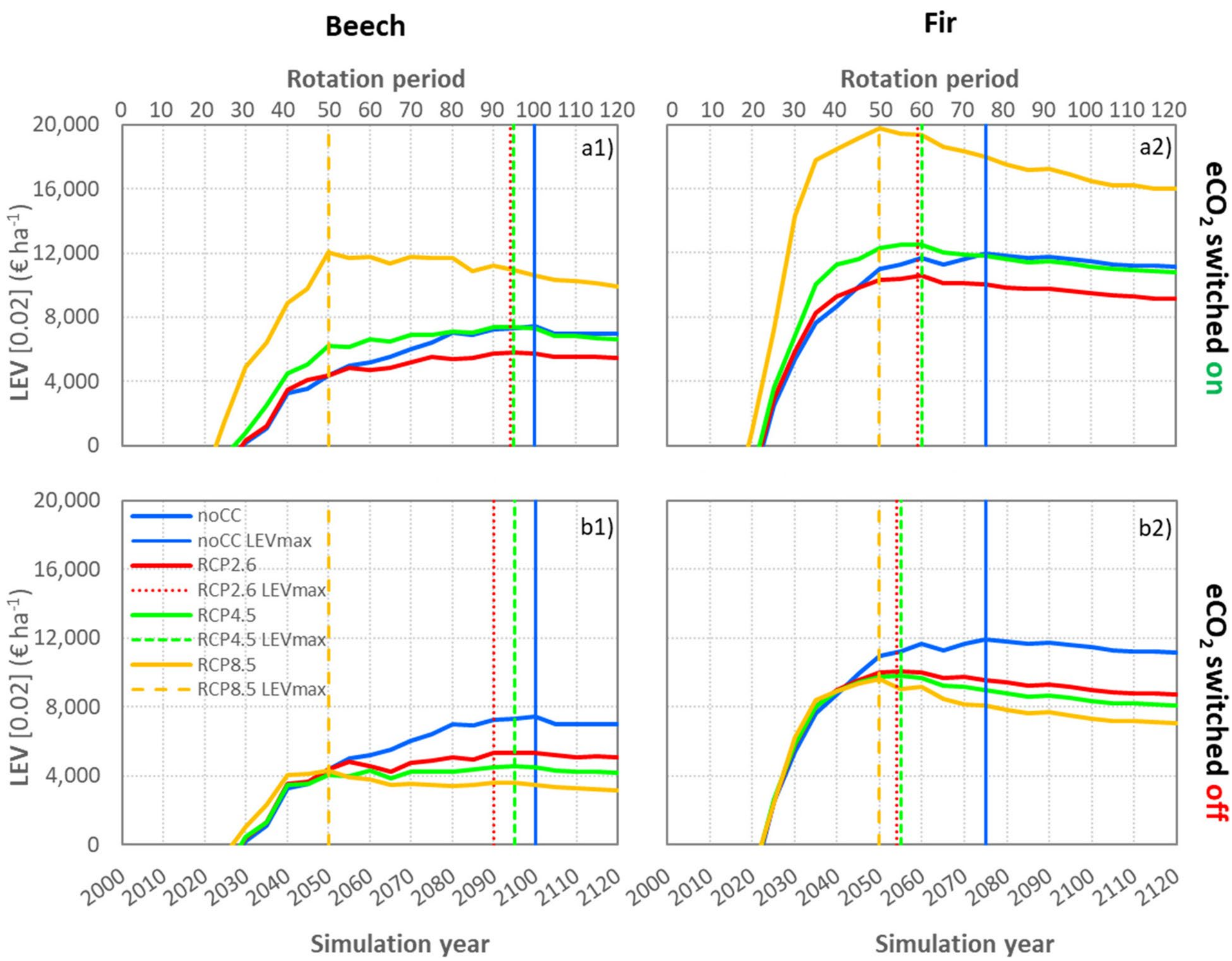

Fig. 4 Evolution of land expectation value (LEV at $i=0.02$) under three climate change (CC) scenarios (RCP2.6, RCP4.5, RCP8.5) of beech (1) and fir (2). Simulation year is displayed on the primary *x*-axes (below) and rotation periods on secondary *x*-axes (above). Vertical lines indicate maximum LEV for optimal rotation and final harvest. Simulations started at bare land with natural regeneration (no planting costs) in the year 2000. CC scenarios were run with eCO_2 switched on (**a**) and off (**b**). The control scenario noCC is displayed for comparison. Only positive LEV values are displayed for better visibility

RCP8.5: it was 62 and 65% higher than in the reference scenario noCC and the optimal rotation age (R_{opt}) was 50 and 25 years shorter for beech and for fir (respectively) (Fig. 4a1, a2). RCP2.6, however, decreased LEV_{max} (12–32%). R_{opt} for fir was reduced 15 years, but remained unchanged for beech. RCP4.5 had neutral effects on LEV_{max} (−2 to + 5%), but reduced R_{opt} 5 years for beech and 15 years for fir. In RCP4.5, the effects of positive eCO_2 and increasing aridity on LEV_{max} were thus balanced. In summary, the LEV in RCP8.5 stayed well above noCC until the end of the simulation period while it fall notably below the reference scenario in RCP2.6 whereas the effects by RCP4.5 were neutralized. The tipping points were 2045 and 2055 in RCP2.6, 2075 and 2100 in RCP4.5 for fir and for beech (Table 2). Similar results were obtained calculating the NPV or annuities instead of LEV (9. Figs. 20 and 21). For NPV, R_{opt} was generally later than for LEV.

Natural regeneration is, however, not always successful and exorbitantly rising establishment costs (can make investments unprofitable). Figure 5 and 9. Fig. 18 show the results of the sensitivity analyses of the effects of costs and discounting factor on LEV without climate change. The marginal costs to still generate a positive LEV (at $i=0.02$) were 9912 € for fir and 6.427 € for beech (9. Fig. 18). The internal rate of return (IRR) at which the LEV became zero—assuming natural regeneration thus zero establishment costs—were 0.054 for beech and 0.063 for fir. With increasing costs, the IRR was gradually reduced. RCP2.6 generally reduced and RCP8.5 increased

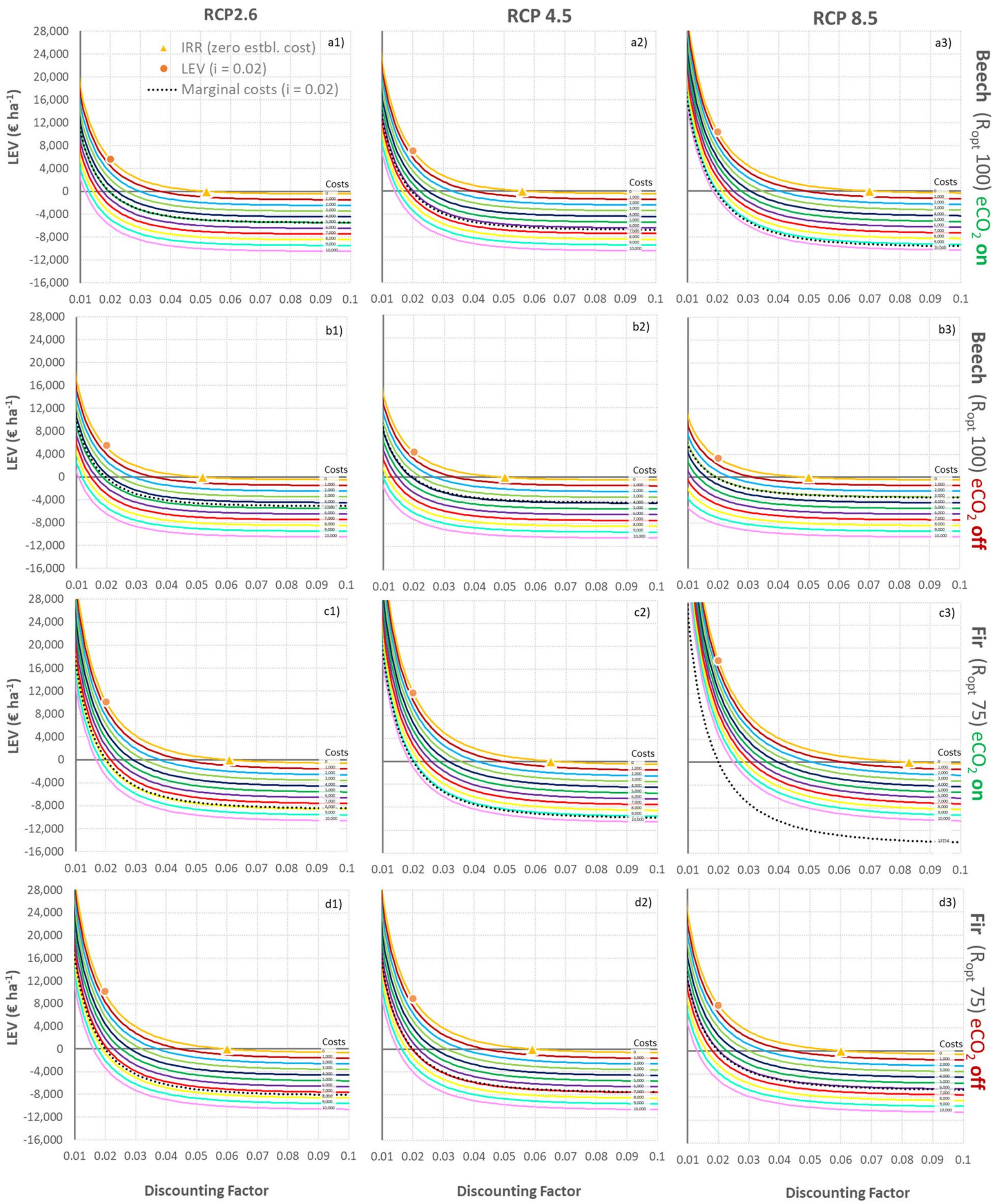

Fig. 5 Sensitivity analyses of the effects of costs and discounting factor on LEV of beech and fir under three climate change (CC) scenarios (RCP2.6, RCP4.5, RCP8.5) with eCO_2 switched on and off. LEV at $i = 0.02$ represents the land expectation value at zero establishment costs Optimal rotation (R_{opt}) according to LEV is 100 for beech and 75 for fir. Dotted lines show the marginal costs when the LEV at i = 0.02 becomes zero. The internal rate of return (IRR) displays when the LEV becomes zero (zero establishment costs)

the marginal costs while RCP4.5 resulted in similar marginal costs than in noCC (Fig. 5). Similar to the marginal costs, the IRR was slightly reduced by RCP2.6, almost not affected by RCP4.5 and notably increased by RCP8.5 (Fig. 5). Decreasing marginal costs and IRR reflect the increasing economic risks under climate change.

3.3 Estimating the CO_2 fertilization effect on the forest value

When eCO_2 was switched off, notably higher economic losses were generated in LEV compared to climate scenarios with eCO_2 enabled. RCP8.5 turned from the most profitable to the least profitable scenario (Fig. 4). LEV_{max} of fir were reduced 20, 23 and 26% for fir and 30, 40 and 52% for beech in RCP 2.6, RCP 4.5 and RCP 8.5 (respectively). R_{opt} was reduced between 15 and 25 years for fir and 0 and 5 years for beech (Fig. 4). De-activating the CO_2 fertilization effect with 100% photosynthetic down-regulation (PD100) but keeping eCO_2 switched on dampened the losses in LEV_{max} between 5 and 7% compared to CO_2 switched off—especially for RCP8.5 (10–14%) (9. Fig. 19) due to the improved water-use efficiency (not shown). The tipping points when the LEV fall below the reference scenario noCC were identical across all CC scenarios: simulation year 2045 for fir and 2050 for beech (Table 2).

Switching off eCO_2 reduced the marginal costs and also the IRR in all scenarios compared to noCC (Fig. 6). This reflects the higher economic risks when climate change unfolds with no positive CO_2 fertilization effect.

3.4 Uncertainty of economic and ecological variables on LEV_{max} and optimal rotation age

Figure 6 shows the effect of CC optimal rotation at various discounting factors. R_{opt} was reduced most strongly when high discounting factors were combined with the most negative climate change impacts (RCP8.5 with eCO_2 switched off). We then analysed the relative contribution in the uncertainty of the LEV from economic and ecological assumptions. Economic parameters contributed to a much higher uncertainty in the LEV than climate change as shown by the split violin plots for beech and fir with boxplots (Fig. 7). The economic uncertainty included five discounting factors (0.01–0.05), two scenarios for high and low timber prices (see "2.3") and establishment and protection costs for fir—since beech easily regenerates in most areas naturally. The uncertainty from climate change originated from six climate scenarios

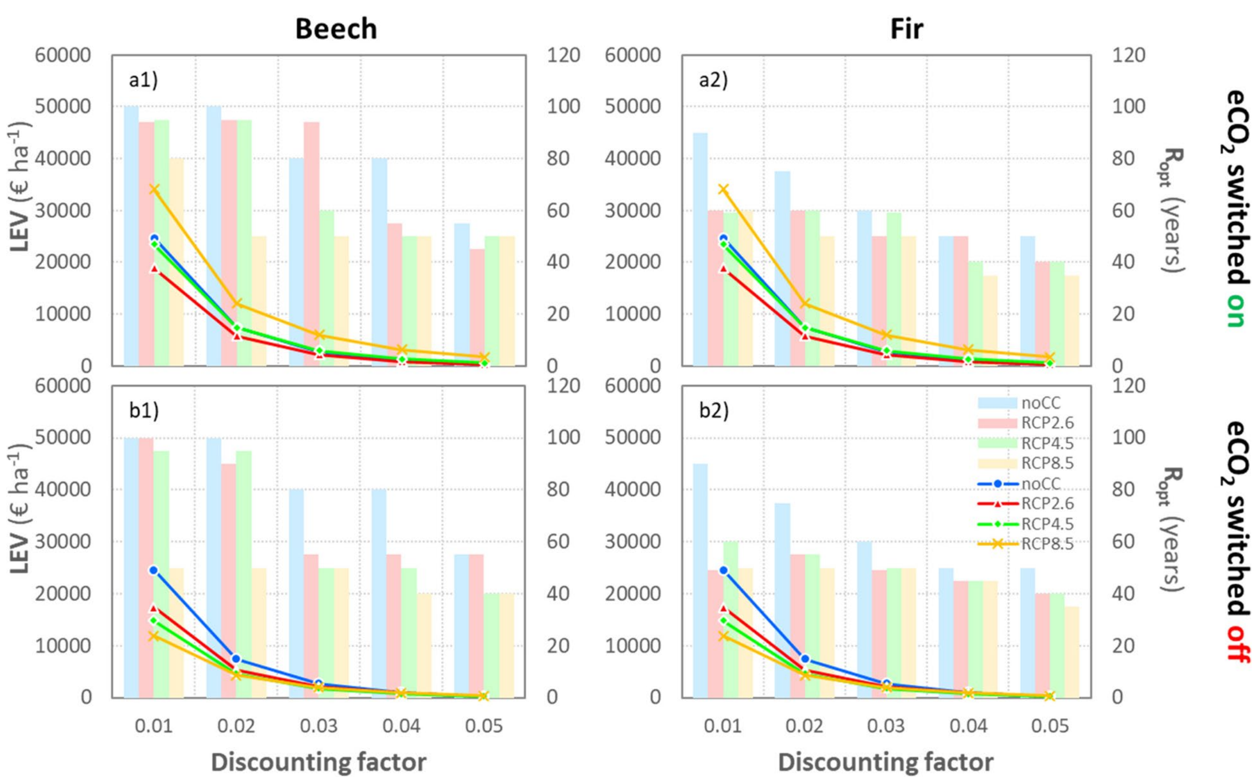

Fig. 6 Influence of five discounting factors on land expectation value (LEV, lines, *y*-axes left) and on optimal rotation age (R_{opt}, columns, *y*-axes right) of beech (1) and fir (2) under three climate change scenarios (RCP2.6, RCP4.5, RCP8.5) with eCO_2 switched on (**a**) and off (**b**). The reference scenario noCC is displayed for comparison. Lines represent the LEV and columns the R_{opt}

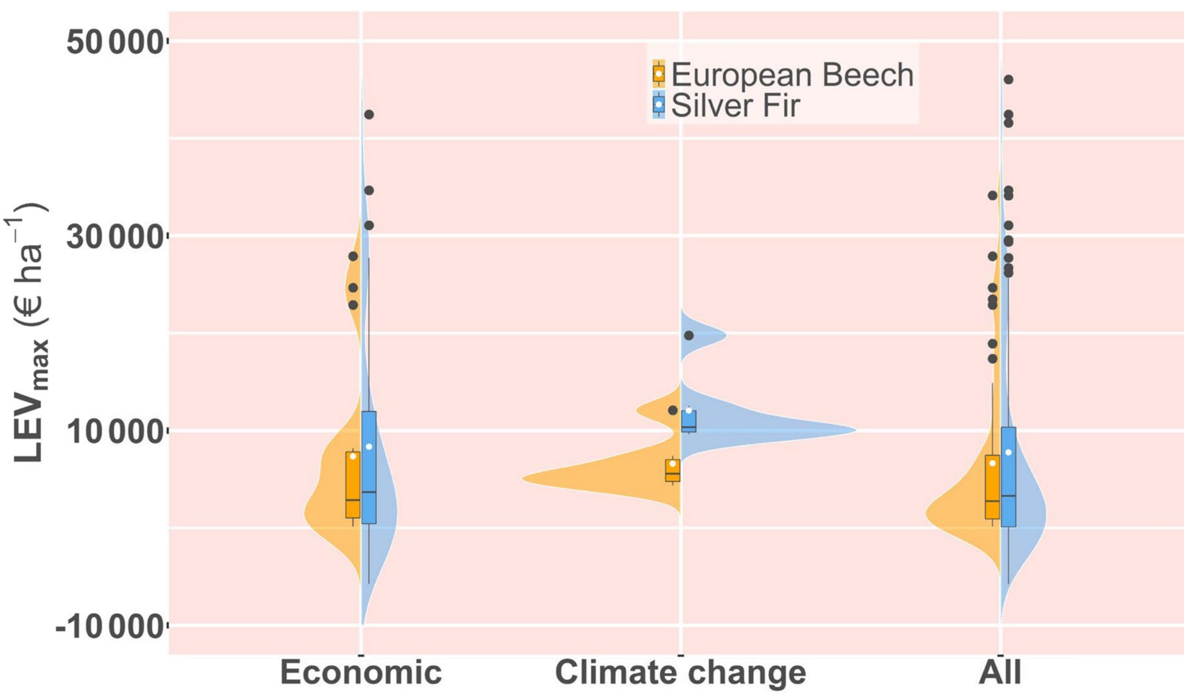

Fig. 7 Split violin plots with boxplots displaying the climate change uncertainty (RCP2.6, RCP4.5, RCP8.5 with eCO_2 switched on and off), economic uncertainty (five discounting factors 0.01–0.05, two scenarios for high and low timber prices, for fir additionally planting costs and protection costs) and uncertainty of all scenarios combined on LEV_{max} of beech (left violin split) and fir (right violin split). White dots represent mean value

(RCP2.6, RCP4.5, RCP8.5 with eCO_2 switched on and off). Within the climate change scenarios, the effect of eCO_2 contributed to the highest uncertainty (9. 22a). Within the economic scenarios, the effect of discounting factors contributed to the highest uncertainty (9. 22b).

3.5 Economic evaluation of admixing fir into beech stands as adaptation strategy

We analysed fir admixture as potential adaptation strategy for beech forests and evaluated under which conditions this would generate an economic benefit compared to pure beech stands. We used the NPV (and not LEV) because fir is generally managed in shorter rotation cycles than beech. The admixture of fir into beech was most profitable at the early juvenile stage of beech increasing the NPV between 7 and 19% compared to a pure beech stand (Fig. 8) (ignoring any protection costs of the fir plantation). A higher share of fir led to a higher NPV. Planting fir in beech stands with increasing stand age of beech gradually cancelled out the added value of fir admixture. At the critical stand, age 50 or older the admixture did not compensate anymore the establishment costs and the NPV fell below the pure beech stand (Fig. 8).

Excessive browsing of fir is, however, often leading to regeneration failure and requires protection costs of the planted saplings for example by fencing or application of tree shelters. The costs of a lower-priced game fence (2000 € per ha) exceeded the added value of admixed fir and the NVP of the mixed stand was reduced between 16 and 30% compared to pure beech (Fig. 8c). When applying costs of tree shelters instead of fencing, the NPV of the mixed stand was 5 and 16% lower due to costs of tree shelters (Fig. 8d). In the mixing ratio 55:45, the costs of tree shelters equalized the costs of fencing and decreased with decreasing share of admixed fir. The marginal costs were reached at less than 900 tree shelters per ha compared to a pure beech stand.

This pattern was conserved under climate change (independent if CO_2 was switched on or off): The admixture of fir created an added value only with cost-neutral hunting. Additional protection costs via fencing or tree shelters, however, nullified the benefit of fir admixture compared to a pure beech stand that was established by natural regeneration (Fig. 9).

4 Discussion

The growth performance and resilience of beech and fir is under debate and ranges from future target species to climate change losers (Klopčič et al. 2017; de Wergifosse

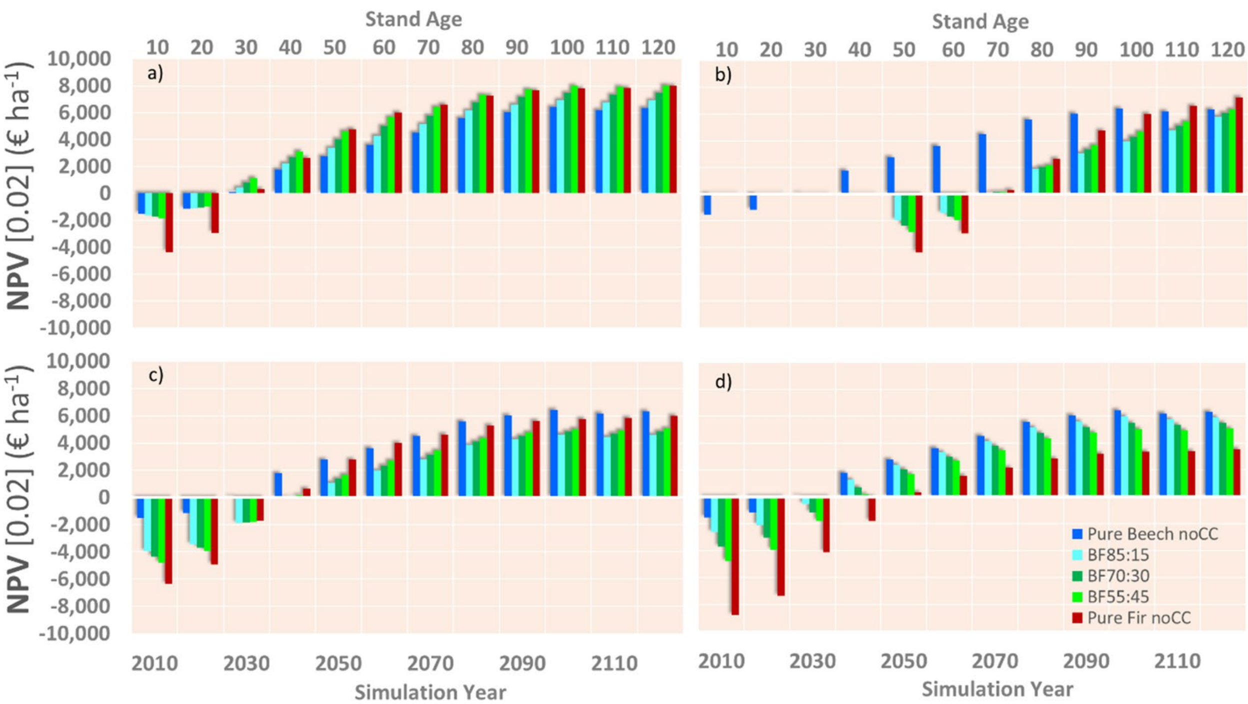

Fig. 8 Impact on net present value of fir admixture into naturally regenerated beech stand (Beech 100%). Three scenarios of species shares of beech-fir (BF) were analysed: 85:15, 70:30 and 55:45. We used the climate file of the reference scenario ignoring CC impacts (noCC). Early admixture with planting costs in juvenile beech is displayed in **a**, the break-even point for a late fir admixture at stand-age 50 in **b**, fir admixture with planting and fencing costs in **c** and fir admixture with planting and tree shelter costs in **d**. Calculated tree density of admixture per ha was 1600 trees per ha

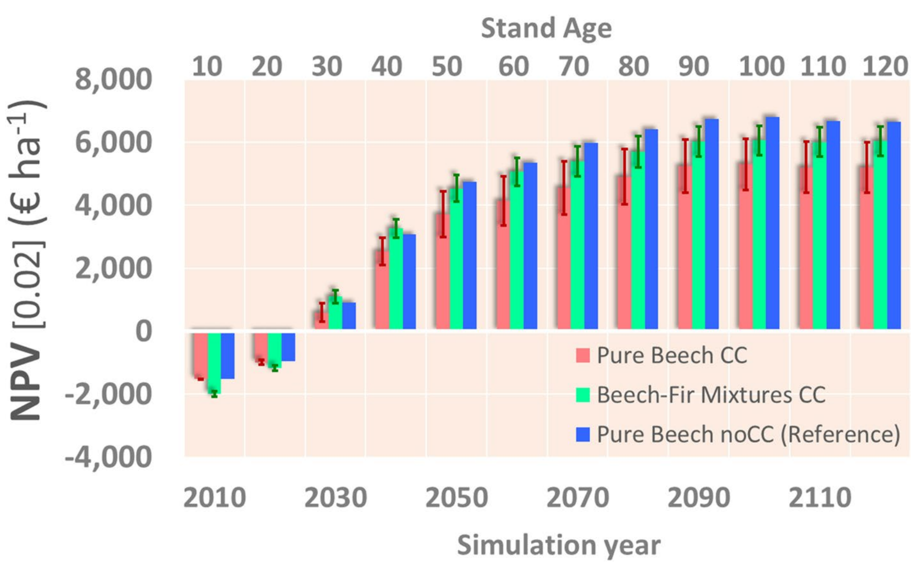

Fig. 9 Mean effect of six climate scenarios and three admixture scenarios on net present value (at $i = 0.02$) of beech forests. Climate scenarios were averaged including RCP2.6, RCP4.5, RCP8.5 with and without eCO_2. Species shares of three admixture scenarios of fir were averaged including 85:15, 70:30, 55:45 (beech:fir). Fir was admixed in juvenile beech stands accounting for planting costs. We assumed cost-neutral hunting to control ungulate browsing. Error bars "Pure Beech CC" represent standard error of six climate change scenarios. Error bars in "Beech-Fir Mixtures CC" represent standard error of six CC and three admixture scenarios. Pure beech stands without climate change serves as reference scenario (Pure Beech noCC). Stand age and simulation year are displayed in primary and secondary *x*-axes, respectively

et al. 2020). The past 4 years have led to increased crown defoliation, drought-induced mortality and bark beetle calamities for fir and beech (FOREST EUROPE 2020; FVA-BW 2020; Schuldt et al. 2020; BMEL 2022b). Yet increasing growth trends have been witnessed in the past century related with nitrogen and CO_2 fertilization in European forests (Norby and Zak 2011; Pretzsch et al. 2014; Zaehle et al. 2014). We investigated when and how climate change can cancel out these gains in productivity and whether fir admixture is economically beneficial adaptation strategy for beech forests under climate change.

4.1 Economic impact of eCO_2 and the cost of climate change

Following our objectives A) and B), this study was conducted in the sub-mountainous belt of the black forest as a test case for other regions with increasing drought risk under future climate change (Sperlich et al. 2020) and where beech and fir naturally co-occur. Our simulation results are representative for stands that were established approximately at the beginning of this century (simulation start in 2000) to reflect beech stands that are currently in the juvenile development phase and that would mature and complete one rotation at the turn to the twenty-second century. Many forest managers are or will be facing a similar situation due to the currently high share of beech (30%) in the natural regeneration in Germany (BWI 2012; BMEL 2016). In this development phase, forest managers are still able to introduce silvicultural changes at manageable business risks because investments that have gone into naturally regenerated beech stands at this stage are still low. We acknowledge, however, that in reality there may occur more silvicultural or technical difficulties to introduce a slower-growing fir after 4–5 m and potentially more tending costs that we have blended out here for simplicity. We found that the applied climate change scenarios increased productivity of beech and fir, but only up to a tipping point (between 2040 and 2070) after which forest productivity notably declined and mortality increased up to 4.5 times compared to our reference scenario (Sperlich et al. 2020). Accumulated drought effects eventually outplayed growth-enhancing CO_2 fertilization towards the end of the century—as projected also by other studies (Piao et al. 2013; Hickler et al. 2015; Reyer 2015; Reyer et al. 2017). Yet, forest profitability, as expressed by the LEV, was not necessarily reduced. This depended much on the eCO_2 fertilization effect. The scenario with the highest eCO_2 (RCP8.5) increased the LEV for both species between 62 and 65% despite growth trends start to decline in 2060 (compared to noCC). RCP2.6, on the other hand, had the lowest eCO_2 levels and generated losses in LEV between 12 and 32%. We highlight that the positive effect of CO_2 fertilization thus persisted much longer in the LEV even when productivity had begun to decline. This lag effect and the gains in profitability under RCP8.5 were generated because the enhanced growth before the tipping point were "stored" in accumulated, standing timber volume. Secondly, the discounting factor enforced the economic benefit of the early productivity gains before the tipping point under eCO_2 and the opposite after the tipping point.

Switching off eCO_2 reversed the results entirely: RCP8.5 turned from the most profitable to the least profitable scenario underlining the great uncertainty regarding the CO_2 fertilization effect not only on productivity, but also economy. Switching off eCO_2 can be considered unrealistic in the same vein as running simulations with eCO_2 switched on. The effect of eCO_2 fertilization will certainly lay somewhat between these two extremes and may decline over time due to limitations of water, nutrients, etc. and acclimatization (Vitale et al. 2007; Norby et al. 2010; Liu et al. 2019; Wang et al. 2020). This was reflected in varying degrees of photosynthetic down-regulation as applied in Sperlich et al. (2020) (and see 9. Figs. 15–17). Tree species with tap root systems (such as fir) and access to deeper soil water reservoirs may benefit more from eCO_2 despite increasing aridity (Nadal-Sala et al. 2021), but may suffer equally on south-facing slopes and/or on more shallow soils.

4.2 What are the consequences for forest management?

The cultivation of beech and fir was—despite significant losses—still profitable generating positive LEVs (at $i=2\%$) even under the worst climate scenario. Most of our applied scenarios lead to economic losses and adaptation of management plans will become inevitable to reduce these losses. Our results generally suggest a shorter rotation cycle under climate change—which is supported by findings of Zamora-Pereira et al. (2021). R_{opt} of fir was 15–25 years shorter across all scenarios whereas for beech R_{opt} was nearly unaffected by RCP2.6 and RCP4.5. The less sensitive response of beech was, in part, due to the greater target diameter for harvesting and its slower growth. RCP8.5, however, drastically shortened R_{opt} by 50 years. The strong eCO_2 effect in RCP8.5 benefitted an earlier harvest and disadvantaged longer rotation because the tipping point for productivity was before stand age 60 (year 2060) and productivity decreased strongly thereafter.

We thus project that forests that were established at the turn of the millennium or before may still benefit from the enhanced productivity as witnessed in the past century (Pretzsch et al. 2014). Forest owners can currently benefit by increasing harvesting volumes, reaching faster target diameters being able to shorten rotation. Forests that are established currently or in time to come and that will reach their target diameter beyond the tipping point will likely witness the opposite: longer rotation to reach target diameters, decreasing harvesting volumes, increasing mortality rates and decreasing profitability. This effect is reinforced with slower-growing hardwood species with longer rotation such as beech.

Shortening rotation as adaptation strategy is, however, a highly controversial and debated question (Knoke and Moog 2005; Bolte et al. 2009; Zanchi et al. 2014; Roberge et al. 2016; Knoke et al. 2020) because it may compromise alternative ecosystem goods and services characteristic of old growth forests (Zanchi et al. 2014; Roberge et al. 2016; Kolo et al. 2020). Yet, shorter production cycles decrease age-dependent natural risks (pests/diseases, windthrow, red heartwood formation, etc.) (Knoke 2003; Staupendahl and Möhring 2011)—irrespective of profitability maximization. The projected increased aridity for the study area (Sperlich et al. 2020), is especially risky for trees older than 60 which show more often crown defoliation or mortality (BMEL 2022b). This rather supports the idea of shortening rotation in commercial forest management to avoid drought-induced die-offs of the older trees close to their target diameter and avoiding losses in economic revenue (Zamora-Pereira and Hanewinkel 2021). In essences, forest practitioners aiming at reducing potential economic losses and increasing their forest resilience will have to reduce critical factors on all three dimensions: target diameter, height and rotation.

Climate change certainly adds another great risk to silvicultural investments and a new debate is needed on how to reconciliate economic objectives with conflicting ecological and socio-economic demands. Diversification of forest management regimes has been suggested to secure the multi-functionality of our forests (Knoke et al. 2017a; Augustynczik et al. 2019). Forest managers may intensify timber production in some areas to satisfy timber needs while reducing management interventions in other areas securing a more natural development focusing on biodiversity, retention forestry and deadwood/habitat trees. Species mixtures may additionally reduce risks according to the Modern Portfolio Theory (Friedrich et al. 2019). Establishing mixed forests are thus among the most prominent adaptation strategies to climate change, but discussions focus mostly on ecological potentials and limitations (Forrester et al. 2013; Bravo-Oviedo et al. 2014; Pretzsch et al. 2019; Schwarz and Bauhus 2019; Bonn et al. 2020).

4.3 Reflection on the use of the LEV approach under climate change

Climate change simulations with process-based models while explicitly quantifying economic implications of including or excluding eCO_2 fertilization have not been done so far and are a novel contribution of this research. The LEV approach sums the series of negative and positive discounted cash flows stemming from management interventions over an infinite number of rotation cycles and provides the mathematical correct solution to determine the optimal rotation. This approach requires, however, a stable economic, socio-economic and environmental framework. Yet, assuming a stable framework over the lifetime of temperate trees—easily encompassing rotation periods of 80 to120 years or longer—has always been a shortcoming of this approach. Climate change, however, violates this assumption much more because the pace at which environmental growth conditions change is heavily accelerating (IPCC 2018) as shown in the following.

At the start of the century, climate change resulted in productivity gains and higher cash-flows due to moderately increasing temperatures, lengthening of the vegetation period and eCO_2. Towards the end of century, increasing drought and heat stress counterbalanced positive eCO_2 resulting in notable growth depression reduced cash-flows. Applying here the LEV approach can be considered logically inconsistent because the succession from productivity gains to losses will not repeat endlessly representing unique climate circumstances of this century. Yet, in the same vein it is highly doubtful to assume a stability of the projected future drier and warmer climate past this century. Environmental conditions have changed tremendously also in the past with appr. 280 ppm atmospheric CO_2 in the eighteenth century (MacFarling Meure et al. 2006) to currently 424 ppm as of May 2023 (NOAA-GML 2023) together with nitrogen depositions leading reportedly to growth increases (Spiecker 1999; Kahle et al. 2008; Pretzsch et al. 2014).

Other approaches that we applied such as transforming the LEV into annuities (yearly fixed income streams) did not overcome the shortcomings of LEV assumptions. Using alternatively the NPV approach did not overcome the shortcomings of solving mathematically correct for the optimal rotation while bearing similar shortcomings of long-term investment calculation such as the LEV approach. Yin and Newman (1997) applied a flexible profit functions that is able to model continuously output supply and input demand (Yin and Newman 1997; Li et al. 2020). However, their work was based on different economic data for industrial and non-industrial private forest owners in the U.S. Coastal Plain region that is not available in our study region. Also, in the context of our research questions and objectives, it was not possible to investigate how output supply and input demand would develop under the course of climate change with all the uncertainties, e.g. extreme events and disturbances, productivity changes, eCO_2, drought, their interplay. Declining discounting rates

(DDR) is considered another alternative to the problem of standard discounting and LEV which, however, attracts a whole new set of assumptions and problems in the decision-making process and makes valuation in forestry even more demanding (Groom et al. 2005; Hepburn and Koundouri 2007; Knoke et al. 2017b).

We chose the pragmatic LEV approach because it can still be understood by forest practitioners and because of our simulated forest problem starting our simulation in the year 2000 with natural regeneration without plantation costs. Gains from initial productivity increases are arguably overestimating the LEV because they would be occurring only once and would unlikely be repeating in the future which is intrinsically assumed by the LEV approach. For our research questions, the relative differences between scenarios were more important. Also, this overestimation became negligible (except for one scenario RCP 8.5 eCO_2 on) because productivity gains were in the young development stage at the start of century while it was at the value-generating second half of the century when climate change led to severe productivity losses. This is when the target diameter with the highest timber prices were reached and over 90% of the cash-flows occurred.

Maybe we are in a phase of a post-Faustmann resource economics as Kant puts it (Kant 2013). We add to this discussion our view that LEV can still be a decision-variable especially when quantifying the relative differences between simulated scenarios (Augustynczik et al. 2017). We explicitly used the LEV and not the NPV because we wanted to address also the optimization problem. We suggest to use the LEV less so as the sole criteria for profit-maximization and rotation-optimization, but rather as an action corridor as one of many criteria on which basis opportunity costs of alternative management options and rotation periods can be evaluated—as elaborated in paragraph 4.2. For other management problems, such as admixing Silver fir into beech forests, other decision variables such as the NPV is more appropriate because the variable rotation of the two species precludes the use of the LEV which requires equally long, infinitely repeating rotation cycles.

4.4 Admixing Silver fir into beech forests—a smart adaptation strategy under climate change?

Admixing silver fir has been suggested as ecologically effective strategy to adapt beech forests to climate change because it may improve its growth performance and drought resilience due to overyielding und potentially due to the effect of hydraulic redistribution (Zang et al. 2014; Vitali et al. 2017; Baumbach et al. 2019; Magh et al. 2019; Schwarz and Bauhus 2019; Töchterle et al. 2020). We focused on an active adaptation strategy based on native species in a socio-economic acceptable framework (Bolte et al. 2009; Almeida et al. 2018).

We found that despite the high establishment costs (plant material, planting) fir admixture payed off and increased the NPV within the time horizon of one rotation of beech (120 years), but only if two critical conditions were met: (i) moderate establishment costs assuming cost-neutral hunting and (ii) early admixture in young beech stands. This result was conserved in all climate change scenarios (Fig. 7). Break-even of the fir admixture was at stand age 50 of beech. This critical stand age may increase or decrease with changes in discounting factors and timber prices. Yet, speed is of the essence for forest owners thinking of admixture as an adaptation strategy. This can have simple practical and technical reasons to establish with shelter cuts enough space and light for the admixture. As a shade-tolerant species, fir plantations may thrive well under beech shelter. Yet, regular tending operations may be necessary so that the plantings are not overgrown by competitive beech regeneration. The pressing need to adopt measures is underlined by the fact that the share of beech has rapidly increased dominating the natural regeneration already with 30% of the species share in Germany (BMEL 2016).

Fir is the most heavily browsed tree species in Europe often leading to regeneration failure (Senn and Suter 2003; Bernard et al. 2017; Vitasse et al. 2019). Natural regeneration in combination with cost-neutral hunting is possible (as assumed above), but remains challenging and requires a strict hunting policy over decades with monitoring and careful analysis of the hunting success (Hagen et al. 2017). In another admixing scenario, we assumed excessive browsing pressure and applied tree shelters or costlier fencing to protect the plantation. Although tree shelters were costlier per ha basis, they can be applied flexibly and became cheaper than fencing being applied in smaller numbers in our admixing scenarios. Yet, the added values were nullified in both cases and the NPV of the beech-fir mixture fall below the pure beech stand.

Establishing costs were thus the bottleneck of creating profitable mixed forest but also timepoint of admixture. Besides often overlooked is the fact that the profitability of admixing strategies strongly depends on the reference stand: Beech admixture into fir stands would obviously have the opposite effect. Our focus lay on beech due to its wider distribution range and its dominance in the natural regeneration. In publicly owned forests, species admixture may be an acceptable opportunity cost to create productive and also ecologically stable forests, but unlikely for forest owners who prioritize monetary values. Funding schemes for adaptation strategies particularly with Silver fir are starting to be available in some federal states in Germany (BayStat 2016; Landesforest.RLP 2019). Moreover, more than 800 mio. € have been provided from federal funds for salvage operations, reforestation and forest conversion to climate adapted mixed forests due to the calamities in the recent years (BMEL 2022a) as well as from the recently launched funding programme by the Federal Ministry of Food and Agriculture for climate adapted forest management with 200 mio. € in 2023 (FNR 2023). This extensive funding scheme may create an opportunity for private or communal forest owners to reduce the conversion costs towards ecologically stable, mixed forests.

4.5 Ecological versus economic uncertainty

The uncertainty in the climate change scenarios stem from two major factors and their interplay: (i) increased severity and frequency of drought due to precipitation decline and temperature increase, and (ii) CO_2 fertilization effect due to eCO_2—the latter being the greatest contributor within the climate uncertainty (9. Fig.22). Previous reports confirm accelerated forest growth in the past decades (Pretzsch et al. 2014) and the large contribution of the CO_2-fertilization effect (Keenan et al. 2023). Nonetheless, many drought-prone sites such as the sub-montane belt of the Black Forest will likely face a tipping point in the coming decades when productivity will decline (Sedmáková et al. 2019) and mortality will increase (Brodribb et al. 2020).

CO_2 fertilization was clearly a major source of uncertainty. Yet, economic assumptions affected the LEV much stronger—mainly due to variable discounting factors and establishment costs, but less so timber prices. While it is clear that lower discounting factors decrease R_{opt} and increase LEV and vice versa at higher interest (e.g. Hanewinkel 2009; Yang et al. 2015), we additionally showed the interaction of discounting factors and establishment costs with climate change which is crucial.

We found that the risks imposed by climate change generally reduced the IRR and the marginal costs. Climate scenarios generally led to shorter rotation, but this effect was cushioned by lowering the discounting factor. For instance, lowering the interest below 1.72% reduced the R_{opt} of beech in RCP8.5 only 20 and not 50 years—as also shown in (Augustynczik et al. 2017). Our results underline the great uncertainty of economic parameters for management decisions under climate change (Augustynczik et al. 2017, 2018) and provides an explanation for the risk behaviour of private forest owners who perceive the business risk of applying adaptation strategies higher than the consequences from climate change (Brunette et al. 2020).

The long residence time of emitted CO_2 in the atmosphere of several hundreds of years means that the projected warmer and drier climate is likely to sustain for longer even if carbon emissions reach a net-zero balance (Knutti and Rogelj 2015). Should this warmer climate be the baseline for infinite considerations such as for the LEV? For this, the forest growth simulation would need to be split with one pathway covering the climate change of this century followed by steady-state of a future warmer, drier climate after this century. Economically this could be expressed with a NPV-based holding value for the first unstable pathway combined with classic LEV calculation for the steady-state period (but discounted to the start of the holding value) as applied, e.g. in forest transition problems (Hanewinkel 2001; Nölte et al. 2018; Vítková et al. 2021). However, the uncertainty band around future climate conditions is wide depending on climate scenarios, but also climate mitigation and adaptation efforts and the efficiency of new technologies, e.g. future carbon-air-capture (Ozkan et al. 2022).

Additional uncertainties can stem from changes in market demands, timber supply, labour costs or technical innovation (Schier et al. 2018; Müller and Hanewinkel 2018). The high and low timber prices due to changes in supply and demand that we have priced in for fir and beech played, however, a minor role in the economic uncertainty confirming other studies (e.g. Augustynczik et al. 2017; Radke et al. 2020). Recent projections point towards a decreasing availability of coniferous timber in the coming decades in parallel with increasing demand and timber prices (Schier et al. 2018) resulting from the continued decline of Norway spruce and the strategy to foster mixed forests with native tree species in Germany (WBW 2020) and Europe (EEA 2016). This supports our assumption of the continued economic benefit from fir admixture in future decades despite periodic price drops due to disturbances. Similarly for beech, increasing demands are projected due to new innovations in wood technology (e.g. cross-laminated timber), which make broadleaves such as beech interesting for new applications in the construction industry—possibly closing the softwood-gap left by abandonment of spruce cultivation (Aicher et al. 2016; Espinoza and Buehlmann 2018; Sciomenta et al. 2021).

5 Conclusions for forest managers

Despite the ecological and economic uncertainties, cultivation of beech and fir was still profitable, although losses in profitability started earliest in 2045. Optimal rotation was generally reduced under climate change—comparatively more for fir than for beech.

Admixing fir into beech created a high economic benefit with cost-neutral hunting and early admixture. Admixture after a stand age 50, however, nullified this benefit the same as costly browsing protection (fencing or tree shelters).

Yet, current funding schemes in Germany can potentially assist private and communal forest owners to stem the business risks associated with costly forest transition and protection. Under the above conditions, we recommend forest systems with time-mixtures of conifers such as fir in broadleaves such as beech to reduce climate change risks and to satisfy future timber needs, and ecological as well as socio-economic demands on suitable sites.

Appendix

Table 3 Definitions of 10 climate change scenarios with (a) base value for atmospheric CO_2 concentration (CO_2 Base), CO_2 increase in % year^{-1}, downregulation factor of photosynthesis (PD), increment of temperature (T increase), decrement of precipitation (P decrease) and concentration factor inducing more intense precipitation events (P factor). In (b), monthly factors of temperature increase (T in °C/100 year) and precipitation decrease (P %/100 year) are listed. Coordinates from the Freiamt site were used to get the data from the MPI-ESM-LR global circulation model from the WorldClim database (http://www.worldclim.org/). Table is taken from Sperlich et al (2020). Gains or loss in forest productivity under climate change? The uncertainty of CO_2 fertilization and climate effects. Climate 8, 141. https://doi.org/10.3390/cli8120141

(a)

Scenario	CO_2 Base	CO_2 Increase	PD	T Increase	P Decrease	P Factor
	ppm	% year^{-1}	%	°C/10 years	%/100 years	-
noCC	370	0	0	0	0	0
RCP 2.6	370	0.21	0	0.18	−24.8	5
RCP 4.5	370	1.38	0	0.25	−23.5	5
RCP 8.5	370	5.36	0	0.44	−26.4	10
RCP2.6-CO2	370	0	0	0.18	−24.8	5
RCP4.5-CO2	370	0	0	0.25	−23.5	5
RCP8.5-CO2	370	0	0	0.44	−26.4	10
RCP8.5_PD100	370	5.36	100	0.44	−26.4	10
RCP8.5_PD75	370	5.36	75	0.44	−26.4	10
RCP8.5_PD50	370	5.36	50	0.44	−26.4	10
RCP8.5_PD25	370	5.36	25	0.44	−26.4	10

(b)

	RCP 2.6		RCP 4.5		RCP 8.5	
Month	T in °C/100 year	P %/100 year	T in °C/100 year	P %/100 year	T in °C/100 year	P %/100 year
1	1.61	14	2.47	14	4.04	16
2	1.01	−22	1.29	−24	3.29	−13
3	0.35	−13	0.56	−4	1.64	−4
4	2	−20	2.07	−4	3.21	−5
5	1.01	−23	1.87	−32	3.37	−29
6	2.46	−20	2.96	−15	5.31	−35
7	2.79	−53	3.86	−63	6.14	−64
8	1.96	−7	3.11	−19	6.18	−32
9	3.15	−44	4.01	−47	6.86	−62
10	1.74	−50	1.96	−38	4.74	−43
11	2.41	−51	3.26	−39	5.34	−37
12	1.36	−9	1.94	−11	3.15	−9

Table 4 Development of land expectation value (a) (LEV), net present value (b) (NPV), and annuities (c) in € per ha at interest rate $i = 2\%$ from establishment till final harvest. Scenario "no climate change" (noCC) is the reference scenario. Climate change scenarios RCP2.6, RCP4.5 and RCP8.5 are run with eCO_2 switched on, eCO_2 switched off and eCO_2 switched on with 100% photosynthetic downregulation. Maximum values for optimal rotation are marked with bold numbers

a1)	Fir		eCO_2 on			eCO_2 off			eCO_2 on PD100		
	Stand age	noCC	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
	5	−17,169.74 €	−16,237.16 €	−16,237.16 €	−16,237.16 €	−16,237.16 €	−16,237.16 €	−16,237.16 €	−16,237.16 €	−16,237.16 €	−16,237.16 €
	10	−12,418.56 €	−11,483.41 €	−11,483.41 €	−11,483.41 €	−11,483.41 €	−11,483.41 €	−11,483.41 €	−11,483.41 €	−11,483.41 €	−11,483.41 €
	15	−5,254.04 €	−4,984.82 €	−4,809.65 €	−4,170.61 €	−5,010.22 €	−4,962.04 €	−4,791.94 €	−5,088.26 €	−5,097.07 €	−5,117.80 €
	20	−2,456.44 €	−2,150.27 €	−1,828.03 €	864.67 €	−2,185.62 €	−2,119.17 €	−1,806.51 €	−2,215.37 €	−2,219.77 €	−2,245.07 €
	25	2,547.65 €	2,917.51 €	3,613.55 €	7,245.56 €	2,501.66 €	2,626.54 €	2,473.03 €	2,457.07 €	2,838.74 €	1,641.55 €
	30	5,423.05 €	5,847.02 €	6,849.69 €	14,277.28 €	5,803.22 €	5,815.25 €	6,201.81 €	5,668.25 €	5,682.75 €	6,014.36 €
	35	7,619.63 €	8,249.46 €	10,071.85 €	17,768.74 €	8,048.53 €	8,052.22 €	8,436.68 €	7,977.18 €	8,064.62 €	8,011.14 €
	40	8,709.39 €	9,276.52 €	11,308.56 €	18,479.45 €	9,012.26 €	8,919.35 €	8,919.17 €	8,898.99 €	8,928.35 €	8,874.68 €
	45	9,928.92 €	9,822.33 €	11,601.98 €	19,165.24 €	9,591.31 €	9,438.92 €	9,345.24 €	9,659.71 €	9,481.16 €	9,466.51 €
	50	10,978.43 €	10,350.73 €	12,297.21 €	**19,754.12** €	10,029.60 €	9,768.22 €	**9,618.44** €	10,071.88 €	9,874.75 €	**10,076.09** €
	55	11,256.57 €	10,412.16 €	12,478.33 €	19,410.07 €	**10,062.87** €	**9,786.02** €	9,021.86 €	**10,099.97** €	**9,974.29** €	9,729.99 €
	60	11,693.64 €	**10,617.13** €	**12,506.79** €	19,333.45 €	10,016.01 €	9,658.40 €	9,163.79 €	10,038.22 €	9,846.02 €	9,648.31 €
	65	11,291.05 €	10,119.46 €	12,050.07 €	18,597.85 €	9,707.50 €	9,241.71 €	8,480.84 €	9,758.17 €	9,451.03 €	9,051.44 €
	70	11,643.15 €	10,120.17 €	11,893.44 €	18,323.61 €	9,730.95 €	9,155.03 €	8,141.41 €	9,798.16 €	9,465.24 €	9,122.47 €
	75	**11,947.33** €	10,060.30 €	11,844.44 €	17,994.47 €	9,578.88 €	8,996.71 €	8,096.62 €	9,683.47 €	9,409.89 €	8,940.60 €
	80	11,829.14 €	9,854.35 €	11,650.32 €	17,502.39 €	9,407.52 €	8,783.18 €	7,852.19 €	9,537.91 €	9,177.87 €	8,732.22 €
	85	11,675.59 €	9,782.55 €	11,448.39 €	17,151.94 €	9,256.36 €	8,601.72 €	7,645.18 €	9,341.79 €	9,028.93 €	8,554.57 €
	90	11,740.64 €	9,794.11 €	11,512.39 €	17,219.89 €	9,334.92 €	8,644.44 €	7,671.26 €	9,415.80 €	9,101.35 €	8,471.42 €
	95	11,607.22 €	9,663.63 €	11,337.07 €	16,866.11 €	9,156.80 €	8,552.19 €	7,522.53 €	9,251.23 €	8,943.55 €	8,270.06 €
	100	11,498.87 €	9,490.54 €	11,166.90 €	16,464.81 €	9,003.59 €	8,347.71 €	7,317.54 €	9,105.79 €	8,834.79 €	8,156.08 €
	105	11,285.06 €	9,343.78 €	10,972.14 €	16,214.55 €	8,857.93 €	8,213.39 €	7,181.06 €	8,961.46 €	8,653.96 €	7,987.04 €
	110	11,242.06 €	9,273.95 €	10,912.10 €	16,185.06 €	8,802.00 €	8,188.70 €	7,175.98 €	8,897.15 €	8,635.04 €	7,891.56 €
	115	11,233.56 €	9,169.48 €	10,875.50 €	16,032.57 €	8,778.48 €	8,150.04 €	7,117.25 €	8,865.55 €	8,601.81 €	7,832.36 €
	120	11,155.00 €	9,160.04 €	10,820.55 €	15,968.71 €	8,725.00 €	8,096.76 €	7,077.76 €	8,806.62 €	8,556.18 €	7,740.56 €
a2)	Beech		eCO_2 on			eCO_2 off			eCO_2 on PD100		
	Stand age	noCC	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
	5	−17,469.88 €	−17,462.96 €	−17,462.96 €	−17,462.96 €	−17,462.95 €	−17,462.95 €	−17,462.95 €	−17,462.96 €	−17,462.96 €	−17,462.96 €
	10	−8,491.34 €	−8,475.13 €	−8,432.81 €	−8,356.95 €	−8,459.60 €	−8,440.20 €	−8,433.05 €	−8,623.14 €	−8,628.24 €	−8,390.46 €
	15	−5,227.76 €	−5,170.59 €	−5,098.84 €	−4,832.38 €	−5,157.06 €	−5,154.26 €	−5,082.35 €	−5,274.98 €	−5,290.91 €	−5,111.17 €
	20	−3,552.57 €	−3,496.67 €	−3,318.83 €	−1,900.55 €	−3,485.54 €	−3,422.62 €	−2,635.61 €	−3,574.14 €	−3,542.83 €	−2,832.32 €
	25	−1,556.86 €	−1,512.31 €	−653.29 €	1,587.83 €	−1,508.52 €	−1,477.38 €	−463.42 €	−1,579.42 €	−1,575.03 €	−1,306.34 €
	30	189.44 €	301.66 €	841.99 €	4,908.99 €	373.49 €	437.70 €	1,021.16 €	352.62 €	378.96 €	587.51 €
	35	1,087.19 €	1,208.83 €	2,556.91 €	6,401.28 €	1,300.10 €	1,308.26 €	2,338.47 €	1,288.77 €	1,306.59 €	1,440.42 €
	40	3,259.37 €	3,456.19 €	4,485.26 €	8,874.56 €	3,511.69 €	3,452.13 €	4,042.95 €	3,517.49 €	3,517.74 €	3,575.09 €
	45	3,528.17 €	4,065.21 €	5,043.62 €	9,760.68 €	3,662.45 €	3,537.87 €	4,106.35 €	3,679.88 €	3,681.96 €	3,651.93 €
	50	4,388.50 €	4,393.59 €	6,189.06 €	**12,072.87** €	4,359.67 €	4,059.58 €	**4,327.75** €	4,393.58 €	4,253.83 €	4,166.62 €
	55	4,989.50 €	4,840.58 €	6,156.84 €	11,707.50 €	4,796.73 €	3,993.93 €	3,953.28 €	4,634.14 €	4,740.45 €	4,095.32 €
	60	5,202.63 €	4,682.72 €	6,630.30 €	11,771.04 €	4,557.07 €	4,282.74 €	3,799.95 €	4,455.60 €	4,541.66 €	4,379.51 €
	65	5,552.73 €	4,847.71 €	6,508.52 €	11,348.74 €	4,255.03 €	3,870.15 €	3,470.90 €	4,319.74 €	4,227.01 €	3,963.08 €
	70	6,012.48 €	5,192.39 €	6,927.29 €	11,763.93 €	4,728.05 €	4,213.37 €	3,554.20 €	4,644.93 €	4,709.06 €	4,303.07 €
	75	6,442.15 €	5,552.22 €	6,923.89 €	11,666.53 €	4,905.91 €	4,239.54 €	3,475.13 €	4,856.74 €	4,890.72 €	4,326.51 €
	80	7,026.34 €	5,398.71 €	7,104.31 €	11,714.40 €	5,099.04 €	4,267.46 €	3,438.59 €	4,994.94 €	5,043.56 €	4,352.09 €
	85	6,922.84 €	5,462.82 €	7,070.02 €	10,885.07 €	4,937.49 €	4,352.94 €	3,473.04 €	4,869.81 €	4,874.78 €	4,435.57 €
	90	7,264.84 €	5,771.64 €	7,369.07 €	11,187.69 €	**5,324.84** €	4,509.86 €	3,619.76 €	5,272.00 €	5,198.96 €	4,590.74 €
	95	7,287.94 €	**5,775.83** €	**7,407.80** €	10,953.45 €	5,301.77 €	**4,573.56** €	3,623.18 €	5,262.55 €	**5,213.53** €	**4,652.93** €
	100	**7,456.27** €	5,764.39 €	7,290.81 €	10,600.12 €	5,319.48 €	4,482.63 €	3,460.51 €	**5,341.51** €	5,119.90 €	4,560.68 €
	105	6,972.08 €	5,564.19 €	6,866.29 €	10,312.93 €	5,199.05 €	4,339.95 €	3,342.90 €	5,163.89 €	5,073.09 €	4,418.42 €
	110	6,979.60 €	5,556.34 €	6,809.76 €	10,226.96 €	5,076.18 €	4,251.13 €	3,277.83 €	5,113.06 €	4,967.05 €	4,328.54 €
	115	6,994.21 €	5,537.59 €	6,695.22 €	10,090.24 €	5,111.14 €	4,243.40 €	3,199.24 €	5,156.83 €	4,936.49 €	4,319.89 €
	120	6,982.83 €	5,463.68 €	6,655.96 €	9,900.97 €	5,052.75 €	4,169.66 €	3,143.14 €	5,064.44 €	4,914.97 €	4,245.34 €

b1)	Fir		eCO_2 on			eCO_2 off			eCO_2 on PD100		
	Stand age	noCC	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
	5	−1,618.58 €	−1,530.66 €	−1,530.66 €	−1,530.66 €	−1,530.66 €	−1,530.66 €	−1,530.66 €	−1,530.66 €	−1,530.66 €	−1,530.66 €
	10	−2,231.02 €	−2,063.01 €	−2,063.01 €	−2,063.01 €	−2,063.01 €	−2,063.01 €	−2,063.01 €	−2,063.01 €	−2,063.01 €	−2,063.01 €
	15	−1,350.21 €	−1,281.03 €	−1,236.01 €	−1,071.79 €	−1,287.55 €	−1,275.17 €	−1,231.46 €	−1,307.61 €	−1,309.87 €	−1,315.20 €
	20	−803.33 €	−703.20 €	−597.82 €	282.77 €	−714.76 €	−693.03 €	−590.78 €	−724.49 €	−725.93 €	−734.20 €
	25	994.78 €	1,139.20 €	1,410.98 €	2,829.17 €	976.82 €	1,025.58 €	965.64 €	959.41 €	1,108.44 €	640.97 €
	30	2,429.14 €	2,619.05 €	3,068.18 €	6,395.21 €	2,599.43 €	2,604.82 €	2,777.97 €	2,538.98 €	2,545.47 €	2,694.01 €
	35	3,809.61 €	4,124.50 €	5,035.65 €	8,883.88 €	4,024.04 €	4,025.89 €	4,218.11 €	3,988.37 €	4,032.09 €	4,005.35 €
	40	4,764.99 €	5,075.27 €	6,187.02 €	10,110.29 €	4,930.69 €	4,879.86 €	4,879.76 €	4,868.72 €	4,884.79 €	4,855.42 €
	45	5,856.11 €	5,793.24 €	6,842.88 €	11,303.72 €	5,656.98 €	5,567.10 €	5,511.85 €	5,697.33 €	5,592.02 €	5,583.38 €
	50	6,899.63 €	6,505.15 €	7,728.45 €	12,414.92 €	6,303.32 €	6,139.05 €	6,044.92 €	6,329.89 €	6,206.00 €	6,332.54 €
	55	7,468.69 €	6,908.43 €	8,279.32 €	12,878.50 €	6,676.67 €	6,492.98 €	5,985.97 €	6,701.29 €	6,617.90 €	6,455.81 €
	60	8,129.63 €	7,381.22 €	8,694.94 €	13,440.96 €	6,963.31 €	6,714.69 €	6,370.83 €	6,978.75 €	6,845.13 €	6,707.68 €
	65	8,174.15 €	7,325.98 €	8,723.64 €	13,463.90 €	7,027.74 €	6,690.53 €	6,139.70 €	7,064.42 €	6,842.07 €	6,552.78 €
	70	8,732.04 €	7,589.85 €	8,919.75 €	13,742.20 €	7,297.94 €	6,866.02 €	6,105.83 €	7,348.35 €	7,098.67 €	6,841.60 €
	75	9,241.76 €	7,782.07 €	9,162.18 €	13,919.48 €	7,409.67 €	6,959.34 €	6,263.08 €	7,490.58 €	7,278.95 €	6,915.93 €
	80	9,402.87 €	7,833.12 €	9,260.73 €	13,912.48 €	7,477.94 €	6,981.67 €	6,241.63 €	7,581.59 €	7,295.40 €	6,941.15 €
	85	9,506.57 €	7,965.21 €	9,321.57 €	13,965.55 €	7,536.77 €	7,003.74 €	6,224.90 €	7,606.33 €	7,351.59 €	6,965.35 €
	90	9,765.14 €	8,146.14 €	9,575.30 €	14,322.45 €	7,764.21 €	7,189.91 €	6,380.48 €	7,831.49 €	7,569.95 €	**7,046.01 €**
	95	9,838.28 €	8,190.89 €	9,609.31 €	14,295.72 €	7,761.31 €	7,248.84 €	6,376.10 €	7,841.35 €	7,580.56 €	7,009.70 €
	100	9,911.64 €	8,180.53 €	9,625.50 €	14,192.12 €	7,760.79 €	7,195.45 €	6,307.48 €	7,848.89 €	7,615.29 €	7,030.27 €
	105	9,874.20 €	8,175.62 €	9,600.39 €	14,187.40 €	7,750.50 €	7,186.55 €	6,283.28 €	7,841.09 €	7,572.04 €	6,988.50 €
	110	9,969.06 €	8,223.82 €	9,676.47 €	14,352.34 €	7,805.30 €	7,261.45 €	6,363.41 €	7,889.68 €	7,657.25 €	6,997.96 €
	115	10,081.44 €	8,229.05 €	9,760.10 €	14,388.26 €	7,878.16 €	7,314.17 €	6,387.30 €	7,956.30 €	7,719.61 €	7,029.07 €
	120	**10,118.79 €**	**8,309.14 €**	**9,815.41 €**	**14,485.34 €**	**7,914.51 €**	**7,344.64 €**	**6,420.29 €**	**7,988.55 €**	**7,761.38 €**	7,021.52 €
b2)	Beech		eCO_2 on			eCO_2 off			eCO_2 on PD100		
	Stand age	noCC	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
	5	−1,646.87 €	−1,646.22 €	−1,646.22 €	−1,646.22 €	−1,646.22 €	−1,646.22 €	−1,646.22 €	−1,646.22 €	−1,646.22 €	−1,646.22 €
	10	−1,525.48 €	−1,522.57 €	−1,514.97 €	−1,501.34 €	−1,519.78 €	−1,516.30 €	−1,515.01 €	−1,549.16 €	−1,550.08 €	−1,507.36 €
	15	−1,343.46 €	−1,328.77 €	−1,310.33 €	−1,241.85 €	−1,325.29 €	−1,324.57 €	−1,306.09 €	−1,355.59 €	−1,359.69 €	−1,313.50 €
	20	−1,161.79 €	−1,143.51 €	−1,085.35 €	−621.53 €	−1,139.87 €	−1,119.29 €	−861.92 €	−1,168.85 €	−1,158.61 €	−926.25 €
	25	−607.91 €	−590.51 €	−255.09 €	620.00 €	−589.03 €	−576.87 €	−180.95 €	−616.72 €	−615.00 €	−510.09 €
	30	84.85 €	135.12 €	377.15 €	2,198.88 €	167.30 €	196.06 €	457.41 €	157.95 €	169.75 €	263.16 €
	35	543.56 €	604.38 €	1,278.38 €	3,200.46 €	650.01 €	654.09 €	1,169.17 €	644.35 €	653.26 €	720.17 €
	40	1,783.23 €	1,890.91 €	2,453.93 €	4,855.36 €	1,921.28 €	1,888.70 €	2,211.94 €	1,924.45 €	1,924.59 €	1,955.97 €
	45	2,080.93 €	2,397.67 €	2,974.74 €	5,756.88 €	2,160.13 €	2,086.65 €	2,421.94 €	2,170.41 €	2,171.63 €	2,153.92 €
	50	2,758.05 €	2,761.25 €	3,889.65 €	7,587.46 €	2,739.93 €	2,551.33 €	2,719.87 €	2,761.24 €	2,673.41 €	2,618.61 €
	55	3,310.51 €	3,211.70 €	4,085.04 €	7,767.88 €	3,182.61 €	2,649.96 €	2,622.98 €	3,074.73 €	3,145.27 €	2,717.23 €
	60	3,616.96 €	3,255.51 €	4,609.51 €	8,183.44 €	3,168.15 €	2,977.44 €	2,641.79 €	3,097.61 €	3,157.44 €	3,044.71 €
	65	4,019.89 €	3,509.50 €	4,711.84 €	8,215.91 €	3,080.43 €	2,801.80 €	2,512.76 €	3,127.27 €	3,060.14 €	2,869.07 €
	70	4,509.19 €	3,894.15 €	5,195.28 €	8,822.62 €	3,545.90 €	3,159.91 €	2,665.55 €	3,483.57 €	3,531.67 €	3,227.18 €
	75	4,983.28 €	4,294.88 €	5,355.92 €	9,024.55 €	3,794.93 €	3,279.46 €	2,688.16 €	3,756.90 €	3,783.18 €	3,346.74 €
	80	5,585.17 €	4,291.38 €	5,647.14 €	**9,311.66 €**	4,053.17 €	3,392.16 €	2,733.30 €	3,970.43 €	4,009.07 €	3,459.43 €
	85	5,636.76 €	4,447.97 €	5,756.60 €	8,862.91 €	4,020.24 €	3,544.28 €	2,827.84 €	3,965.12 €	3,969.17 €	3,611.55 €
	90	6,042.45 €	4,800.49 €	6,129.14 €	9,305.23 €	4,428.88 €	3,751.02 €	3,010.69 €	4,384.93 €	4,324.17 €	3,818.29 €
	95	6,177.26 €	4,895.59 €	6,278.85 €	9,284.15 €	4,493.79 €	**3,876.55 €**	**3,071.01 €**	4,460.54 €	4,418.99 €	**3,943.83 €**
	100	**6,427.06 €**	4,968.71 €	**6,284.43 €**	9,136.95 €	4,585.22 €	3,863.88 €	2,982.84 €	4,604.21 €	4,413.18 €	3,931.15 €
	105	6,100.43 €	4,868.55 €	6,007.86 €	9,023.60 €	4,549.06 €	3,797.37 €	2,924.97 €	4,518.30 €	4,438.85 €	3,866.03 €
	110	6,189.26 €	4,927.17 €	6,038.66 €	9,068.91 €	4,501.38 €	3,769.75 €	2,906.66 €	4,534.08 €	4,404.61 €	3,838.40 €
	115	6,276.88 €	**4,969.65 €**	6,008.55 €	9,055.38 €	**4,586.94 €**	3,808.19 €	2,871.12 €	**4,627.94 €**	4,430.20 €	3,876.84 €
	120	6,334.18 €	4,956.15 €	6,037.67 €	8,981.24 €	4,583.39 €	3,782.33 €	2,851.17 €	4,593.99 €	**4,458.40 €**	3,850.98 €

c1)	Fir		eCO_2 on			eCO_2 off			eCO_2 on PD100		
	Stand age	noCC	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
	5	−343.39 €	−324.74 €	−324.74 €	−324.74 €	−324.74 €	−324.74 €	−324.74 €	−324.74 €	−324.74 €	−324.74 €
	10	−248.37 €	−229.67 €	−229.67 €	−229.67 €	−229.67 €	−229.67 €	−229.67 €	−229.67 €	−229.67 €	−229.67 €
	15	−105.08 €	−99.70 €	−96.19 €	−83.41 €	−100.20 €	−99.24 €	−95.84 €	−101.77 €	−101.94 €	−102.36 €
	20	−49.13 €	−43.01 €	−36.56 €	17.29 €	−43.71 €	−42.38 €	−36.13 €	−44.31 €	−44.40 €	−44.90 €
	25	50.95 €	58.35 €	72.27 €	144.91 €	50.03 €	52.53 €	49.46 €	49.14 €	56.77 €	32.83 €
	30	108.46 €	116.94 €	136.99 €	285.55 €	116.06 €	116.30 €	124.04 €	113.37 €	113.65 €	120.29 €
	35	152.39 €	164.99 €	201.44 €	355.37 €	160.97 €	161.04 €	168.73 €	159.54 €	161.29 €	160.22 €
	40	174.19 €	185.53 €	226.17 €	369.59 €	180.25 €	178.39 €	178.38 €	177.98 €	178.57 €	177.49 €
	45	198.58 €	196.45 €	232.04 €	383.30 €	191.83 €	188.78 €	186.90 €	193.19 €	189.62 €	189.33 €
	50	219.57 €	207.01 €	245.94 €	**395.08 €**	200.59 €	195.36 €	**192.37 €**	201.44 €	197.49 €	**201.52 €**
	55	225.13 €	208.24 €	249.57 €	388.20 €	**201.26 €**	**195.72 €**	180.44 €	**202.00 €**	**199.49 €**	194.60 €
	60	233.87 €	**212.34 €**	**250.14 €**	386.67 €	200.32 €	193.17 €	183.28 €	200.76 €	196.92 €	192.97 €
	65	225.82 €	202.39 €	241.00 €	371.96 €	194.15 €	184.83 €	169.62 €	195.16 €	189.02 €	181.03 €
	70	232.86 €	202.40 €	237.87 €	366.47 €	194.62 €	183.10 €	162.83 €	195.96 €	189.30 €	182.45 €
	75	**238.95 €**	201.21 €	236.89 €	359.89 €	191.58 €	179.93 €	161.93 €	193.67 €	188.20 €	178.81 €
	80	236.58 €	197.09 €	233.01 €	350.05 €	188.15 €	175.66 €	157.04 €	190.76 €	183.56 €	174.64 €
	85	233.51 €	195.65 €	228.97 €	343.04 €	185.13 €	172.03 €	152.90 €	186.84 €	180.58 €	171.09 €
	90	234.81 €	195.88 €	230.25 €	344.40 €	186.70 €	172.89 €	153.43 €	188.32 €	182.03 €	169.43 €
	95	232.14 €	193.27 €	226.74 €	337.32 €	183.14 €	171.04 €	150.45 €	185.02 €	178.87 €	165.40 €
	100	229.98 €	189.81 €	223.34 €	329.30 €	180.07 €	166.95 €	146.35 €	182.12 €	176.70 €	163.12 €
	105	225.70 €	186.88 €	219.44 €	324.29 €	177.16 €	164.27 €	143.62 €	179.23 €	173.08 €	159.74 €
	110	224.84 €	185.48 €	218.24 €	323.70 €	176.04 €	163.77 €	143.52 €	177.94 €	172.70 €	157.83 €
	115	224.67 €	183.39 €	217.51 €	320.65 €	175.57 €	163.00 €	142.34 €	177.31 €	172.04 €	156.65 €
	120	223.10 €	183.20 €	216.41 €	319.37 €	174.50 €	161.94 €	141.56 €	176.13 €	171.12 €	154.81 €
c2)	Beech		eCO_2 on			eCO_2 off			eCO_2 on PD100		
	Stand age	noCC	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
	5	−349.40 €	−349.26 €	−349.26 €	−349.26 €	−349.26 €	−349.26 €	−349.26 €	−349.26 €	−349.26 €	−349.26 €
	10	−169.83 €	−169.50 €	−168.66 €	−167.14 €	−169.19 €	−168.80 €	−168.66 €	−172.46 €	−172.56 €	−167.81 €
	15	−104.56 €	−103.41 €	−101.98 €	−96.65 €	−103.14 €	−103.09 €	−101.65 €	−105.50 €	−105.82 €	−102.22 €
	20	−71.05 €	−69.93 €	−66.38 €	−38.01 €	−69.71 €	−68.45 €	−52.71 €	−71.48 €	−70.86 €	−56.65 €
	25	−31.14 €	−30.25 €	−13.07 €	31.76 €	−30.17 €	−29.55 €	−9.27 €	−31.59 €	−31.50 €	−26.13 €
	30	3.79 €	6.03 €	16.84 €	98.18 €	7.47 €	8.75 €	20.42 €	7.05 €	7.58 €	11.75 €
	35	21.74 €	24.18 €	51.14 €	128.03 €	26.00 €	26.17 €	46.77 €	25.78 €	26.13 €	28.81 €
	40	65.19 €	69.12 €	89.71 €	177.49 €	70.23 €	69.04 €	80.86 €	70.35 €	70.35 €	71.50 €
	45	70.56 €	81.30 €	100.87 €	195.21 €	73.25 €	70.76 €	82.13 €	73.60 €	73.64 €	73.04 €
	50	87.77 €	87.87 €	123.78 €	**241.46 €**	87.19 €	81.19 €	**86.55 €**	87.87 €	85.08 €	83.33 €
	55	99.79 €	96.81 €	123.14 €	234.15 €	95.93 €	79.88 €	79.07 €	92.68 €	94.81 €	81.91 €
	60	104.05 €	93.65 €	132.61 €	235.42 €	91.14 €	85.65 €	76.00 €	89.11 €	90.83 €	87.59 €
	65	111.05 €	96.95 €	130.17 €	226.97 €	85.10 €	77.40 €	69.42 €	86.39 €	84.54 €	79.26 €
	70	120.25 €	103.85 €	138.55 €	235.28 €	94.56 €	84.27 €	71.08 €	92.90 €	94.18 €	86.06 €
	75	128.84 €	111.04 €	138.48 €	233.33 €	98.12 €	84.79 €	69.50 €	97.13 €	97.81 €	86.53 €
	80	140.53 €	107.97 €	142.09 €	234.29 €	101.98 €	85.35 €	68.77 €	99.90 €	100.87 €	87.04 €
	85	138.46 €	109.26 €	141.40 €	217.70 €	98.75 €	87.06 €	69.46 €	97.40 €	97.50 €	88.71 €
	90	145.30 €	115.43 €	147.38 €	223.75 €	**106.50 €**	90.20 €	72.40 €	105.44 €	103.98 €	91.81 €
	95	145.76 €	**115.52 €**	**148.16 €**	219.07 €	106.04 €	**91.47 €**	72.46 €	105.25 €	**104.27 €**	**93.06 €**
	100	**149.13 €**	115.29 €	145.82 €	212.00 €	106.39 €	89.65 €	69.21 €	**106.83 €**	102.40 €	91.21 €
	105	139.44 €	111.28 €	137.33 €	206.26 €	103.98 €	86.80 €	66.86 €	103.28 €	101.46 €	88.37 €
	110	139.59 €	111.13 €	136.20 €	204.54 €	101.52 €	85.02 €	65.56 €	102.26 €	99.34 €	86.57 €
	115	139.88 €	110.75 €	133.90 €	201.80 €	102.22 €	84.87 €	63.98 €	103.14 €	98.73 €	86.40 €
	120	139.66 €	109.27 €	133.12 €	198.02 €	101.06 €	83.39 €	62.86 €	101.29 €	98.30 €	84.91 €

Table 5 Parameters of beech and fir used for different submodules (a–g) in GOTILWA+. Reference indicates the source of the used parameter originating from a pre-setting of GOTILWA+(GOT), the Freiamt (FRA) experimental site in the Black Forest (Germany), measured parameter (meas), calibrated parameter of a pre-setting of GOTILWA+(cal), setting by the user (user). For allometric relationships and wood density in (e) following references were used [1] (Zell et al. 2014), [2] (Nord-Larsen and Nielsen 2015), [3] (Gebauer et al. 2008), [4] (Vejpustková et al. 2015), [5] (Brzeziecki and Kienast 1994), [6] (EOL 2020). (Table from Sperlich et al. 2020)

Parameters for different GOTILWA+Modules (a-g)	Beech	Fir	Unit	Reference
a) Constants				
PAR to global radiation	0.42	0.42	joule/joule	GOT
µEinsteins per watt	4.6	4.6	µE/watt	GOT
Energy equivalence of organic matter	4700	4700	cal/g	GOT
Organic matter to carbon ratio	2	2	g/g	GOT
grams of N per 100 g of dry matter	1.2	1.2	g/g	GOT
Respiration rate of structural components 25 °C	33.3	33.3	cal/g/day	GOT
Respiration rate of non-structural components 25 °C	55.5	55.5	cal/g/day	GOT
Respiration rate of living components of wood 25 °C	35	35	cal/g/day	GOT
Plant tissues formed by 1 g of carbon	0.68	0.68	g/g	GOT
b) Canopy structure				
Longitude	7.93	7.93	GG.mm	FRA
Latitude	48.2	48.2	GG.mm	FRA
Altitude	481	481	m a.s.l	FRA
Slope	36	9	%	FRA
Aspect	17.5	17.5	°	FRA
Albedo of the canopy	0.15	0.076	-	GOT
Leaf PAR absorbance	0.92	0.92	-	GOT
Value X for the ellipsoidal distribution	1.35	1.34	-	GOT
b) Photosynthesis				
V_{cmax} at 25 °C	40	40	µmols/m^2/s	meas
EaVcmax	75,400	75,400	J/mol	GOT
EdVcmax	175,000	175,000	Ppmv	GOT
Vomax at 25 °C	8.4	8.4	µmols/m^2/s	GOT
EaVomax	75,400	75,400	J/mol	GOT
EdVomax	175,000	175,000	Ppmv	GOT
J_{max} at 25 °C	70	75	µmols/m^2/s	meas
EaJmax	65,300	65,300	J/mol	GOT
EdJmax	129,000	129,000	J/mol	GOT
SJmax	420	420	J/mol/°K	GOT
Curvature of the function A_n/PPFD	0.7	0.7	-	meas
K_c at 25 °C	404	404	Pa	GOT
EaKc	59,400	59,400	J/mol	GOT
K_o at 25 °C	248,000	248,000	Pa	GOT
EaKo	36,000	36,000	J/mol	GOT
Compensation point (Γ*) at 25°	42.2	42.2	µmol/mol	GOT
EaGammast	37,830	37,830	J/mol	GOT
R_d at 25 °C	0.69	0.57	µmols/m^2/s	meas
Q_{10} value at 25 °C	2.2	2.2	-	GOT
Mesophyll conductance	Unlimited	Unlimited	-	GOT
c) Stomatal conductance (g_s)				
Residual conductance	0.01	0.01	mols/m^2/s	GOT
Leuning constant (g_1)	7	7	-	GOT
Factor reflecting gs vs. VPD responses (g_{sDO})	0.8	0.8	-	cal

Parameters for different GOTILWA + Modules (a-g)	Beech	Fir	Unit	Reference	
W_{fac}:			-		
Soil water content (SWC) at which $g_s = 0$	15	20	m^3/m^3	cal	
SWC at which $g_s = g_{s,max}$	65	65	m^3/m^3	cal	
Curvature (q) for photosynthetic response function	0.6	0.4	-	GOT	
				GOT	
Leaf characteristical dimension	0.002	0.002	m	GOT	
Parameter X for the ellipsoidal distribution	1.35	1.34	v/h	GOT	
Differencial transpiration rate (tall-short trees)	1.025	1.025	-	GOT	
Trees leaf stomatal type	Hypostomatous	Hypostomatous	-	User	
d) Volatile Organic Compounds (VOC)					
VOC emissions	Monoterpenes	Isoprene & Monoterpene		User	
VOC emission model	Niinemets	Niinemets	-	User	
Isoprens basal emission rate	-	0.00416295	µgramm C/g/h	meas	
Monoterpens basal emission rate	0.01665182	4.829028	µmols C/g/h	meas	
e) Tree structure					
Allometric relationships					
i) DBH—total aboveground biomass	$y = a * DBH^b$				
				Beech	*Fir*
a	0.125	0.1122	-	[1]	[2]
b	2.2215	2.36	-	[1]	[2}
ii) DBH—bark thickness	$y = a * DBH^b$				
a	0.04938	0.049	-	GOT	
b	0.9196	0.9	-	GOT	
				Beech	*Fir*
Wood density	0.6	0.39	g/cm^3	[3, 4, 5]	[5, 6]
Bark density	0.44	0.38	g/cm^3	GOT	
Morphic coefficient (tapering)	0.51	0.83	-	cal	
Leaf area index in closed mature forests	7.5	10	m^2/m^2	meas & cal	
Leaf mass per area	5.72	12	mg/cm^2	meas & cal	
Mean leaf life span	1	5	years		
Maximum mobile carbon stored in leaves	0.17	0.2	%	cal	
Sapwood area in closed forests	20	22	m^2/ha	cal	
Sapflow treshold for cavitation	12	14	$kg/cm^2/year$	GOT	
Fraction of respiring sapwood	0.06	0.06	%	GOT	
Maximum mobile carbon stored in woody organs	0.2	0.2	%	Cal	
Biomass of branches / aboveground biomass	0.18	0.2	kg/kg	Cal	
Fine roots biomass in closed mature forests	280	310	g/m^2		
P/B of fine roots in closed mature forests	1	3	$year^{-1}$	GOT	
Belowground /aboveground biomass	0.133	0.153	kg/kg	Cal	
Gross litterfall/fine litterfall	9	10	g/kg/year	GOT	
Regeneration tree species	Seedler	Seedler	-		
f) Thermal inertia for photosynthesis and SOM decomposition					
Min. temperature threshold for photosynthesis	9	10	°C	cal	
Max. temperature threshold for photosynthesis	15	15	°C	cal	
Thermal inertia for photosynthesis	3	3	-	cal	
temperature threshold for SOM decomposition	9	10	°C	cal	
Max temperature threshold for SOM decomposition	15	15	°C	cal	
Thermal inertia for SOM decomposition	3	3	-	cal	
g) Soil Carbon efflux and Hydrology					
Initial L + F soil organic matter (SOC)	3268	2400	g/m^2	meas	
SOC (% dry weight) in the top layer of mineral soil	5.36	5.00	%		

Parameters for different GOTILWA + Modules (a-g)	Beech	Fir	Unit	Reference
Bulk density (soil column average)	1.96	1.97	g/cm^3	
Maximum soil water holding capacity	119.35	114.62	Mm	
k (L + F)	0.0066	0.0066	day^{-1}	GOT
k (A + B)	0.00005	0.0005	day^{-1}	GOT
Soil Q10	2.2	2.2	-	GOT
L + F to A + B transfer rate	1	1	-	GOT
W min	10	10	mm	GOT
W max	100	100	mm	GOT
Mean soil depth	0.8	0.8	m	meas
Relative volume of stones	32.5	33.0	%	meas
Field capacity (% of max. water filled porosity)	70	70	%	GOT
Drainage rate	0.22	0.22	1/day	GOT
h) Tree density				
Un- or evenaged population	Unevenaged	Unevenaged		user
Response factor to canopy opening	2	2	-	GOT
Mobile C threshold for mortality	30	20	%	cal
DBH classes	2	2	cm	user
Initial DBH	0	0	cm	user
Initial tree density	1200	250	trees/ha	user
Trees per DBH class				
0–2	300	250	-	user
2–4	400	0	-	user
4–6	500	0	-	user

Table 6 Table displaying management interventions in GOTILWA + for beech (a) and fir (b)with the year of intervention, the DBH class of intervention (small, big or all DBH classes), the mode of thinning (trees, basal area, standing volume, or biomass), the intensity of thinning (positive signs indicated the number of thinned trees and negative signs the tree number of the remaining stand after thinning), number of regenerated trees (regeneration), and the total tree number of the stand. Interventions are every five years except for the initialisation period (first 35 years). During the initialisation period a diameter distribution was created calibrated with inventory data from Freiamt (Table from Sperlich et al. 2020)

Year	DBH classes	Thinning mode	Thinning intensity	Regeneration	Tree number
a) European Beech					
2	All	trees	− 500	200	875
6	Big	trees	250	220	823
10	All	trees	− 700	200	900
14	All	trees	− 700	200	901
16	Big	trees	5	100	941
18	Big	trees	5	70	1006
20	All	trees	− 700	70	787
25	All	trees	− 650	70	720
30	All	trees	− 650	70	720
35	All	trees	− 620	70	689
40	All	trees	− 600		597
45	All	trees	− 550		552
50	All	trees	− 530		529
55	All	trees	− 500		499
60	All	trees	− 450		450
65	All	trees	− 400		400

Year	DBH classes	Thinning mode	Thinning intensity	Regeneration	Tree number
70	All	trees	−350		347
75	All	trees	−300		303
80	All	trees	−255		257
85	All	trees	−220		219
90	All	trees	−195		194
95	All	trees	−175		176
100	All	trees	−161		161
105	All	trees	−147	400	547
110	Big	trees	3	400	796
115	Big	trees	3	400	1115
120	Big	trees	3		1112
b) Silver fir					
2	trees	Big	50	800	1000
4	trees	Big	50	900	1850
6	trees	Small	600	0	1250
8	trees	Small	300	300	1250
10	trees	Small	250	250	1250
12	trees	All	200	250	1340
14	trees	All	200		1071
16	trees	All	100	100	1071
18	trees	All	100		980
20	trees	All	50	100	1030
25	trees	All	−800	100	900
30	trees	All	−750	50	800
35	trees	All	−700	50	750
40	trees	All	−650		649
45	trees	All	−562		562
50	trees	All	−495		496
55	trees	All	−437		436
60	trees	All	−389		388
65	trees	All	−345		344
70	trees	All	−296		295
75	trees	All	−256		257
80	trees	All	−220		221
85	trees	All	−189		190
90	trees	All	−163		162
95	trees	All	−138		139
100	trees	All	−115	100	214
105	trees	Big	15	50	249
110	trees	Big	15	50	237
115	trees	Big	17	50	270
120	trees	Big	10	50	270

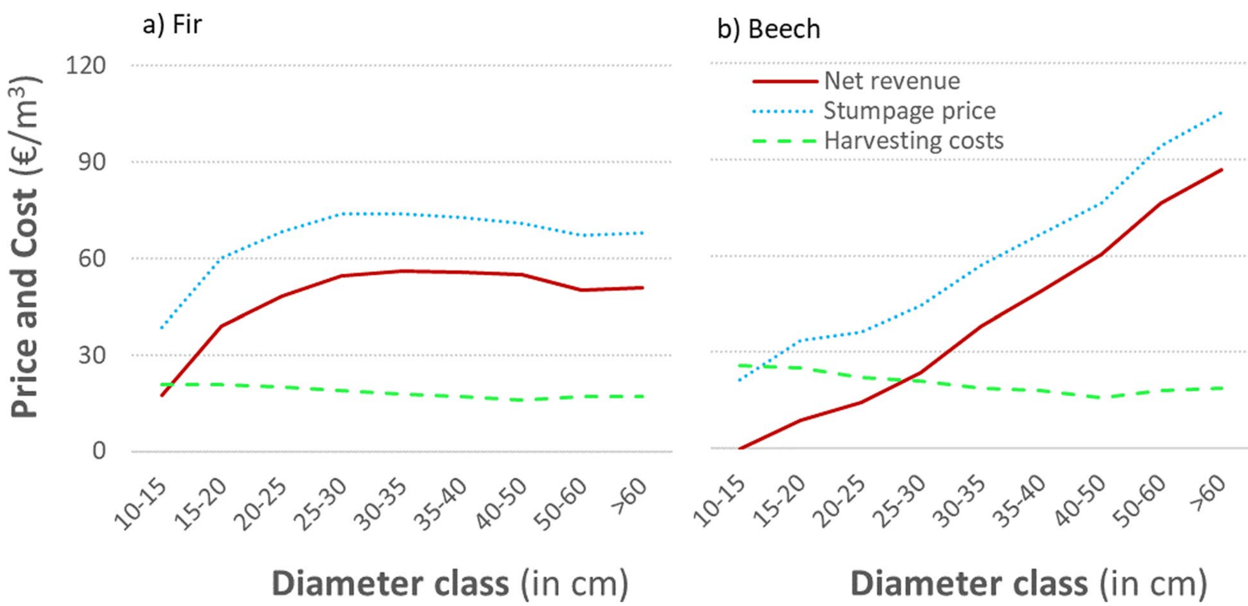

Fig. 10 Wood price, harvesting costs and net revenue per m^3 roundwood for 9 diameter classes of *A. alba* (**a**) and *F. sylvatica* (**b**). Wood prices and harvesting costs are mean values (inflation corrected) for the period 2000 to 2016 for Baden-Württemberg averaged for all wood quality classes

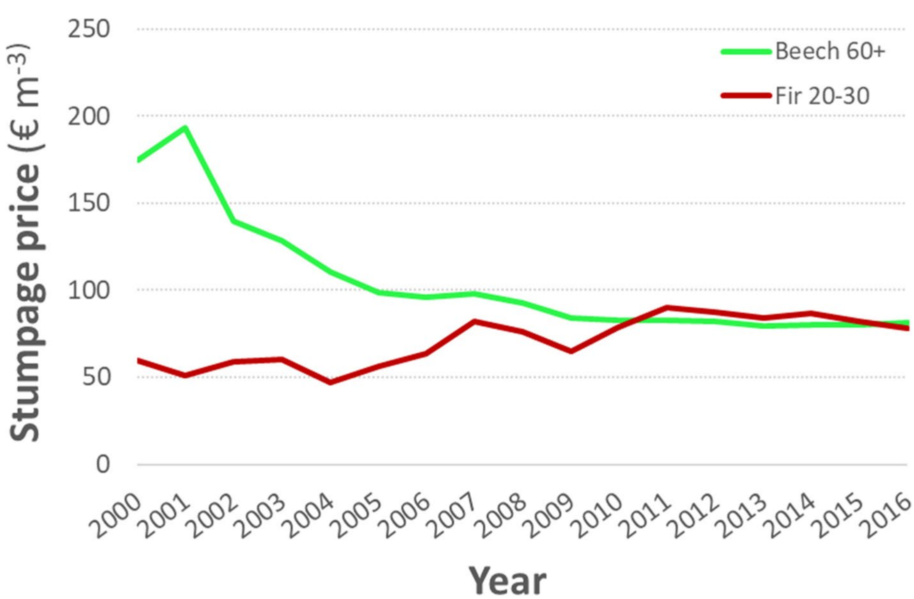

Fig. 11 Net roundwood timber prices (harvesting costs subtracted) for Baden-Württemberg of leading assortments of beech (diameter < 60 cm) and fir (diameter 20–30 cm). Wood prices and harvesting costs were inflation corrected

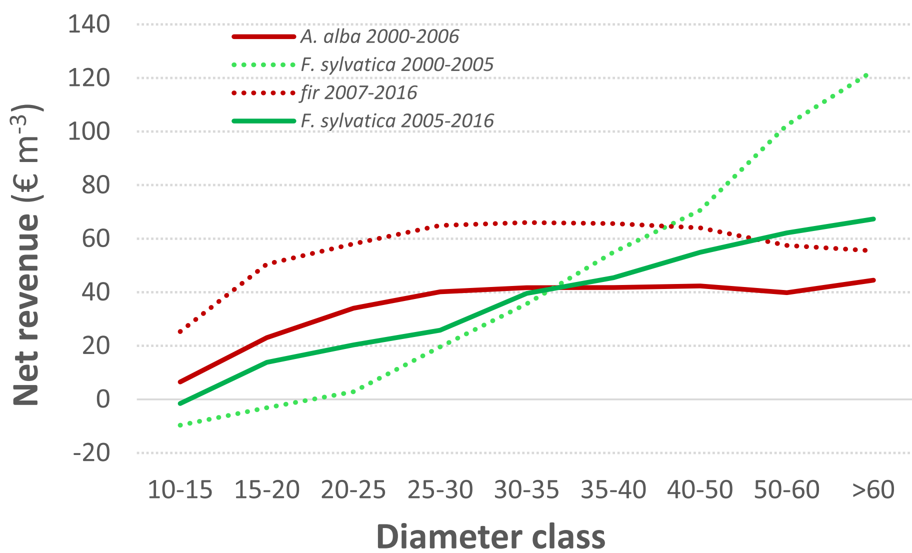

Fig. 12 Net revenue (€ per m^3) of 9 diameter classes of beech and fir roundwood for averaged for all wood quality classes. Periods of high timber prices (2000–2005 for beech and 2007–2016) and low timber prices (2006–2016 for beech and 2000–2006) are displayed

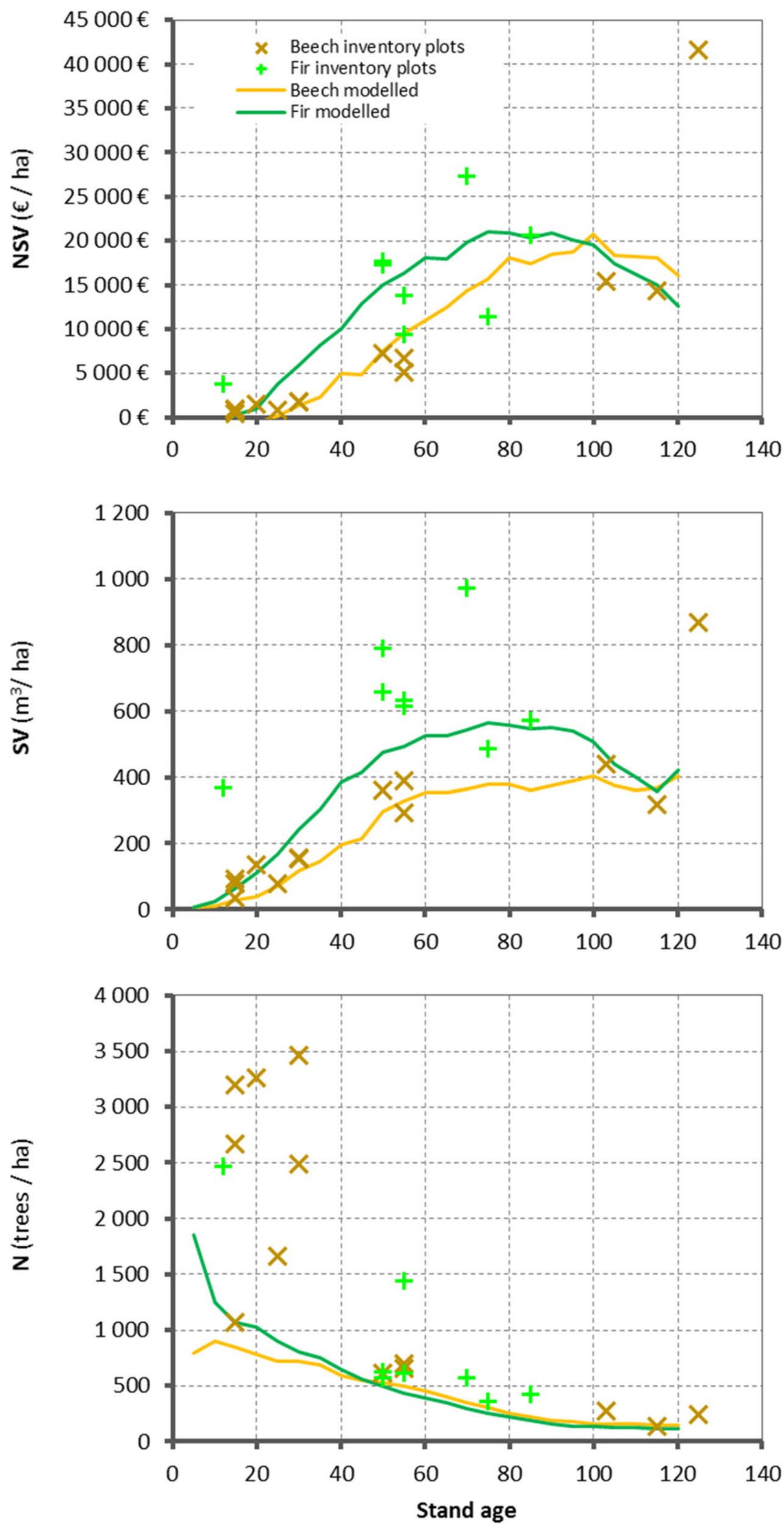

Fig. 13 Net stumpage value (NSV in € ha^{-1}), standing wood volume (SV overbark in m^3 ha^{-1}) and tree density (N) of modelled stands and of inventory plots nearby the Freiamt experimental site

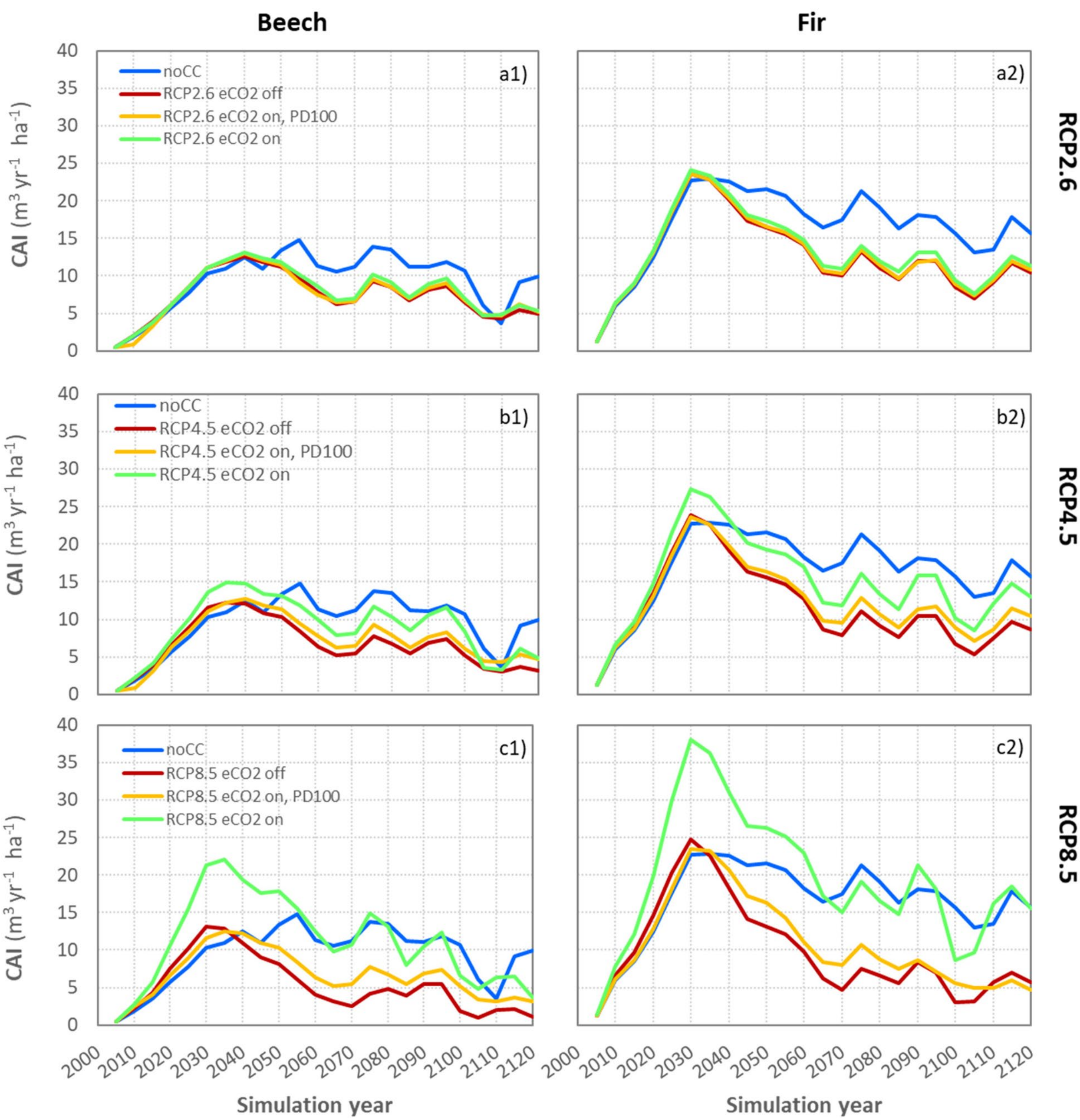

Fig. 14 Effect of three climate change (CC) scenarios (RCP2.6, RCP4.5, RCP8.5) on current annual increment (CAI) of beech (1) and fir (2). CC scenarios were run with eCO_2 switched on, eCO_2 switched off and eCO_2 switched on with 100% photosynthetic downregulation (PD100). The reference scenario noCC is displayed for comparison. Data basis was the simulation output from Sperlich et al. (2020)

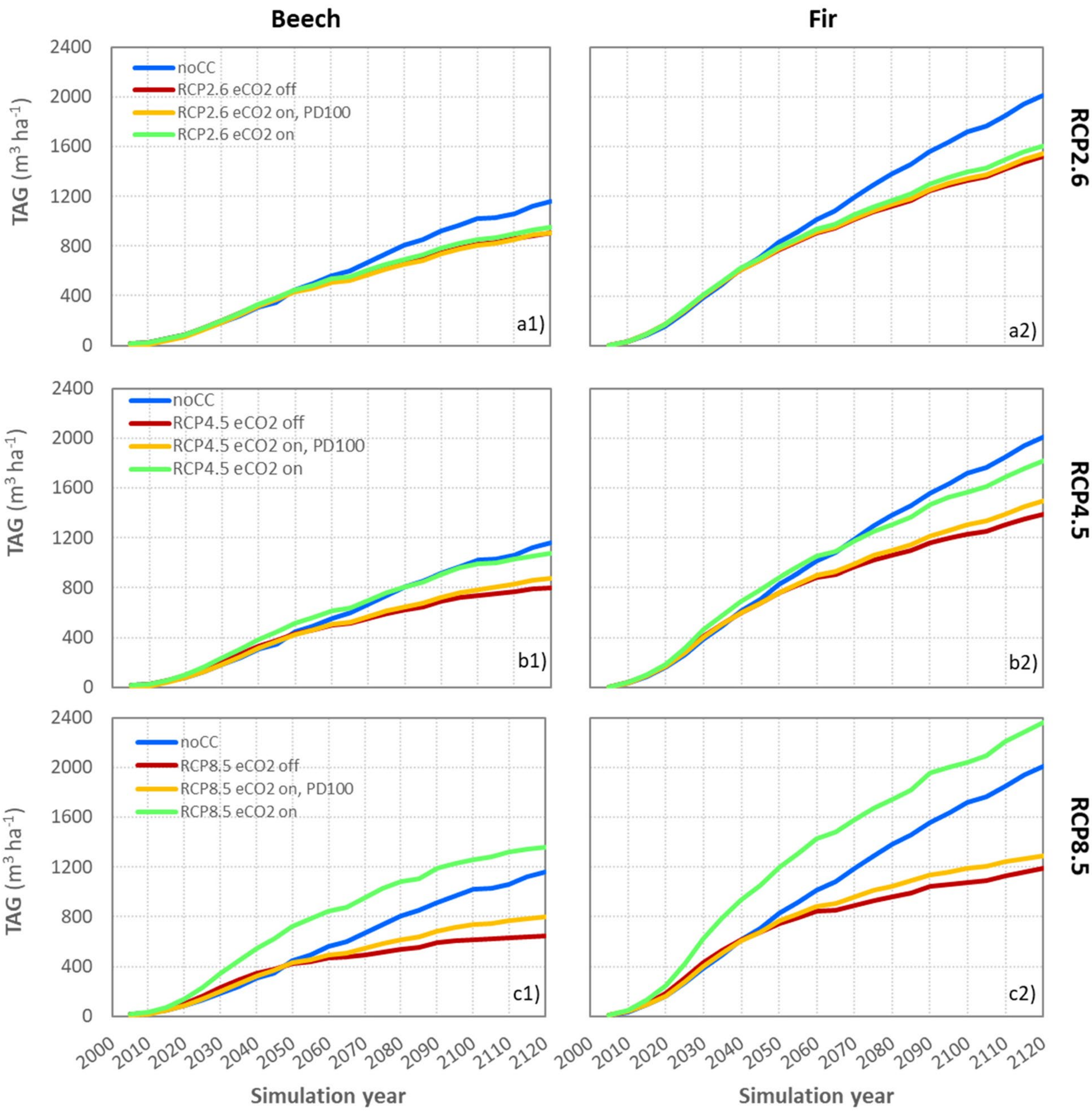

Fig. 15 Effect of three climate change (CC) scenarios (RCP2.6, RCP4.5, RCP8.5) on total accumulated growth (TAG) of beech (1) and fir (2). CC scenarios were run with eCO_2 switched on, eCO_2 switched off and eCO_2 switched on with 100% photosynthetic downregulation (PD100). The reference scenario noCC is displayed for comparison. Data basis was the simulation output from Sperlich et al. (2020). Stand age 0 corresponds to simulation year 2000

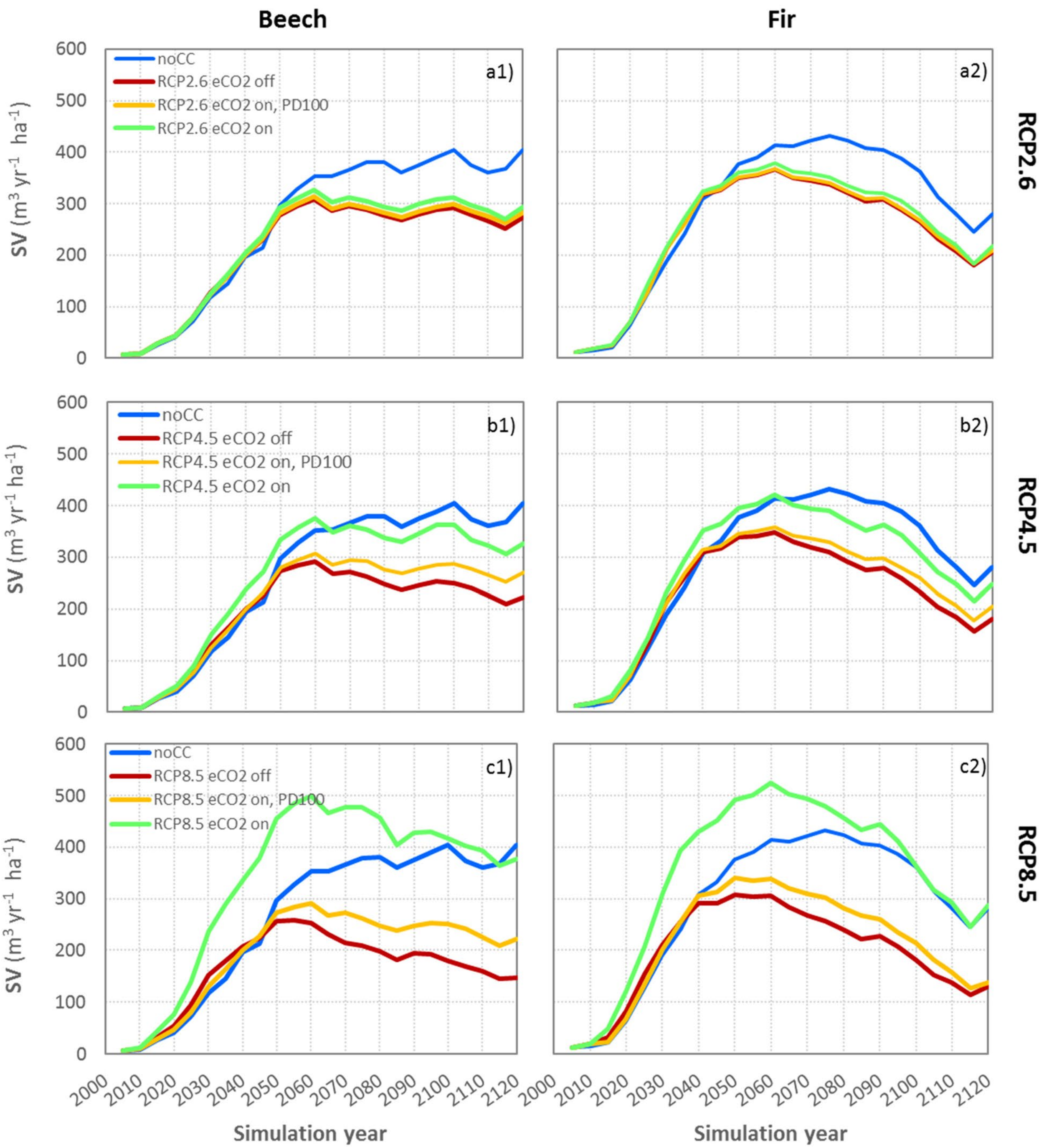

Fig. 16 Effect of three climate change (CC) scenarios (RCP2.6, RCP4.5, RCP8.5) on standing timber volume of beech (**a**) and fir (**b**). CC scenarios were run with eCO_2 switched on (1) and off (2). The reference scenario noCC is displayed for comparison. Data basis was the simulation output from Sperlich et al. (2020). Stand age 0 corresponds to simulation year 2000

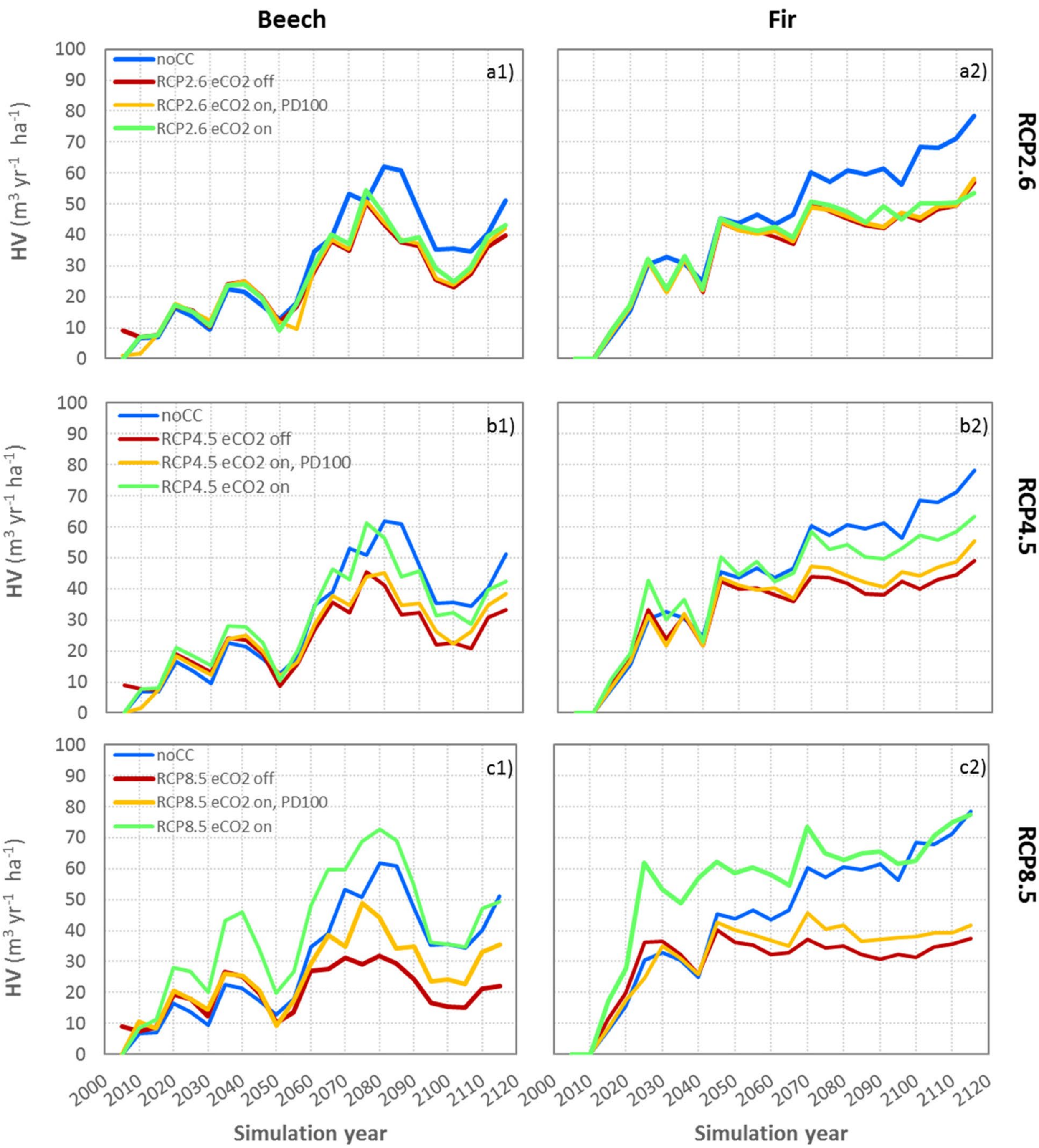

Fig. 17 Effect of three climate change (CC) scenarios (RCP2.6, RCP4.5, RCP8.5) on harvested timber volume of beech (**a**) and fir (**b**). CC scenarios were run with eCO_2 switched on (1) and off (2). The reference scenario noCC is displayed for comparison. Data basis was the simulation output from Sperlich et al (2020). Stand age 0 corresponds to simulation year 2000

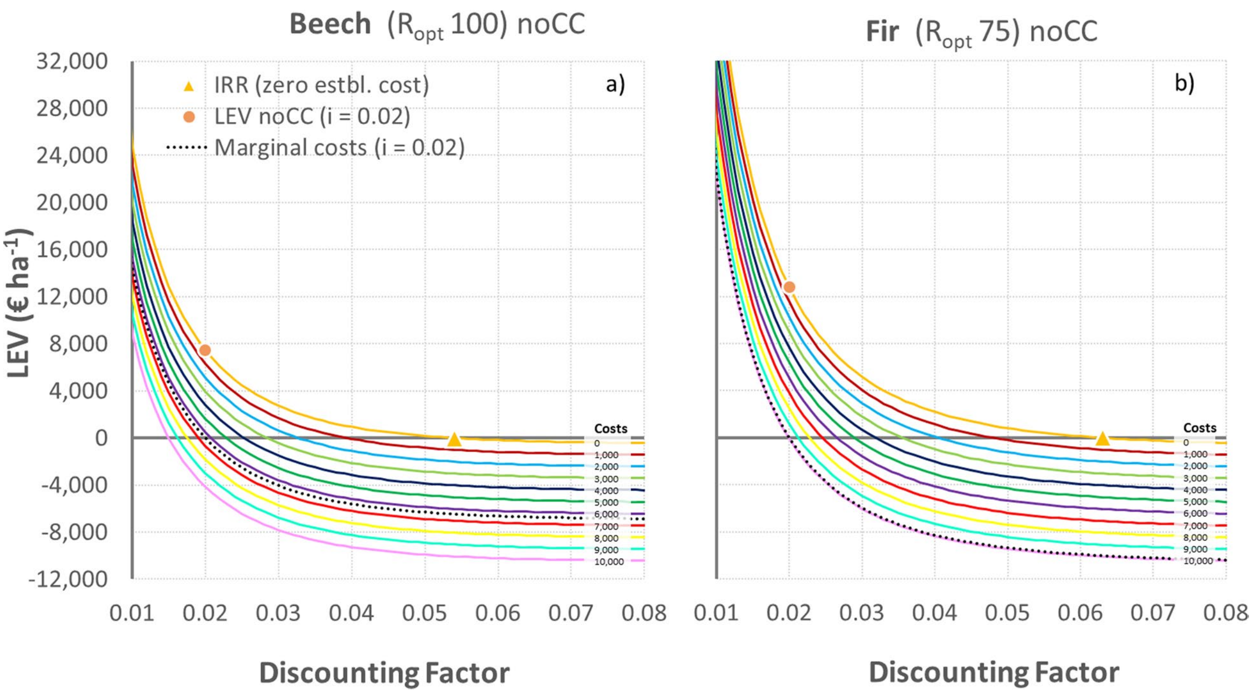

Fig. 18 Sensitivity analyses of the effects of costs and discounting factor on LEV of beech (**a**) and fir (**b**). LEV noCC at $i = 0.02$ represents the reference scenario without climate change and zero establishment costs. Optimal rotation (R_{opt}) according to LEV is 100 for beech and 75 for fir. Dotted lines show the marginal costs when the LEV at $i = 0.02$ becomes zero. The internal rate of return (IRR) displays when the LEV becomes zero (at zero establishment costs)

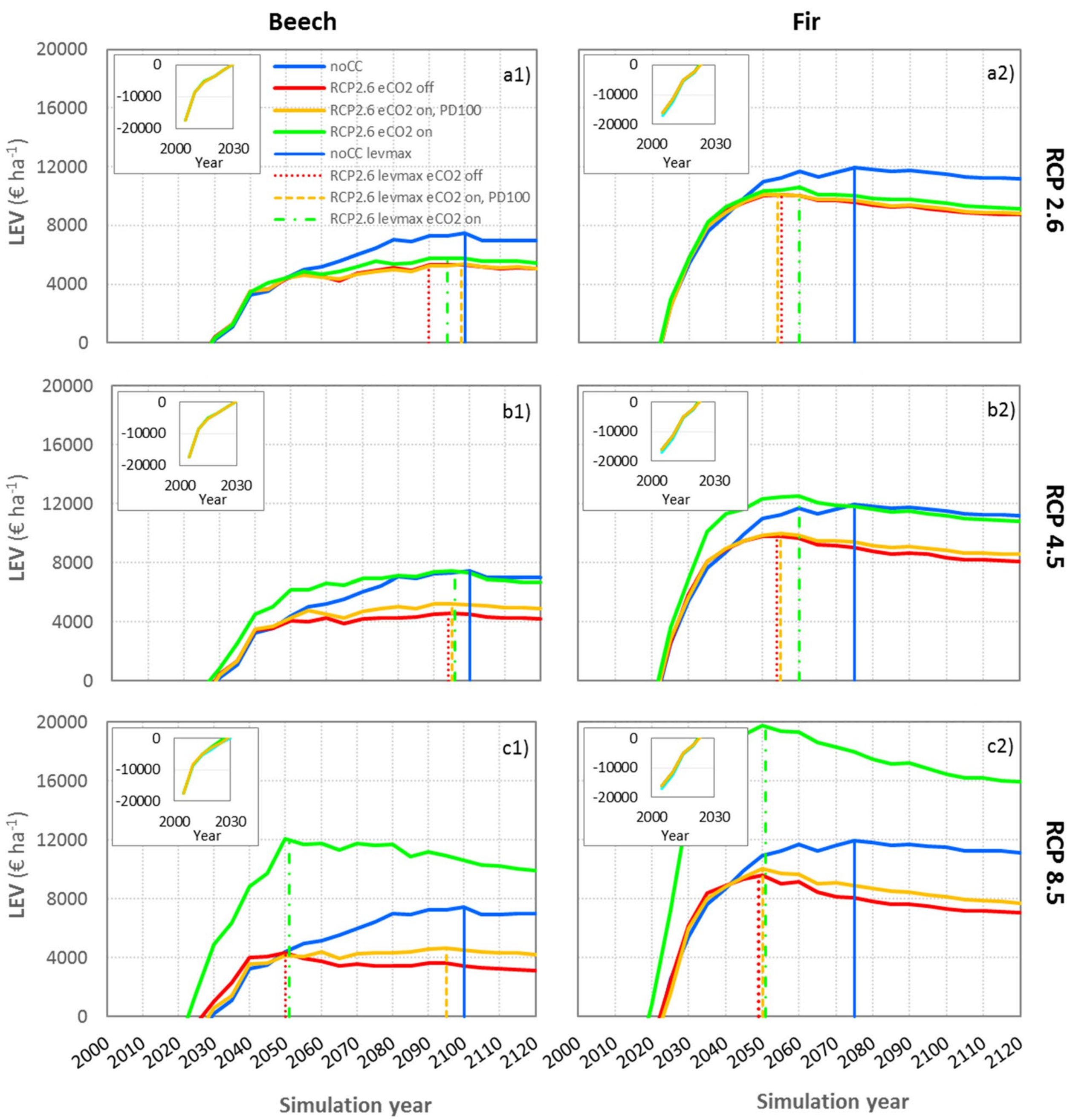

Fig. 19 Effect of climate scenario **a** RCP2.6, **b** RCP4.5 and **c** RCP8.5) on land expectation value (LEV with 2% interest rate) of beech (1) and fir (2) with eCO_2 switched on combined with 100% photosynthetic downregulation (PD100) and with eCO_2 switched off. The control scenario noCC is displayed for comparison. Inset plot show negative LEV values for better visibility. Vertical lines indicate maximum LEV for optimal rotation. Simulations started with naturally regenerated juvenile stands (no planting costs) (stand age 0)

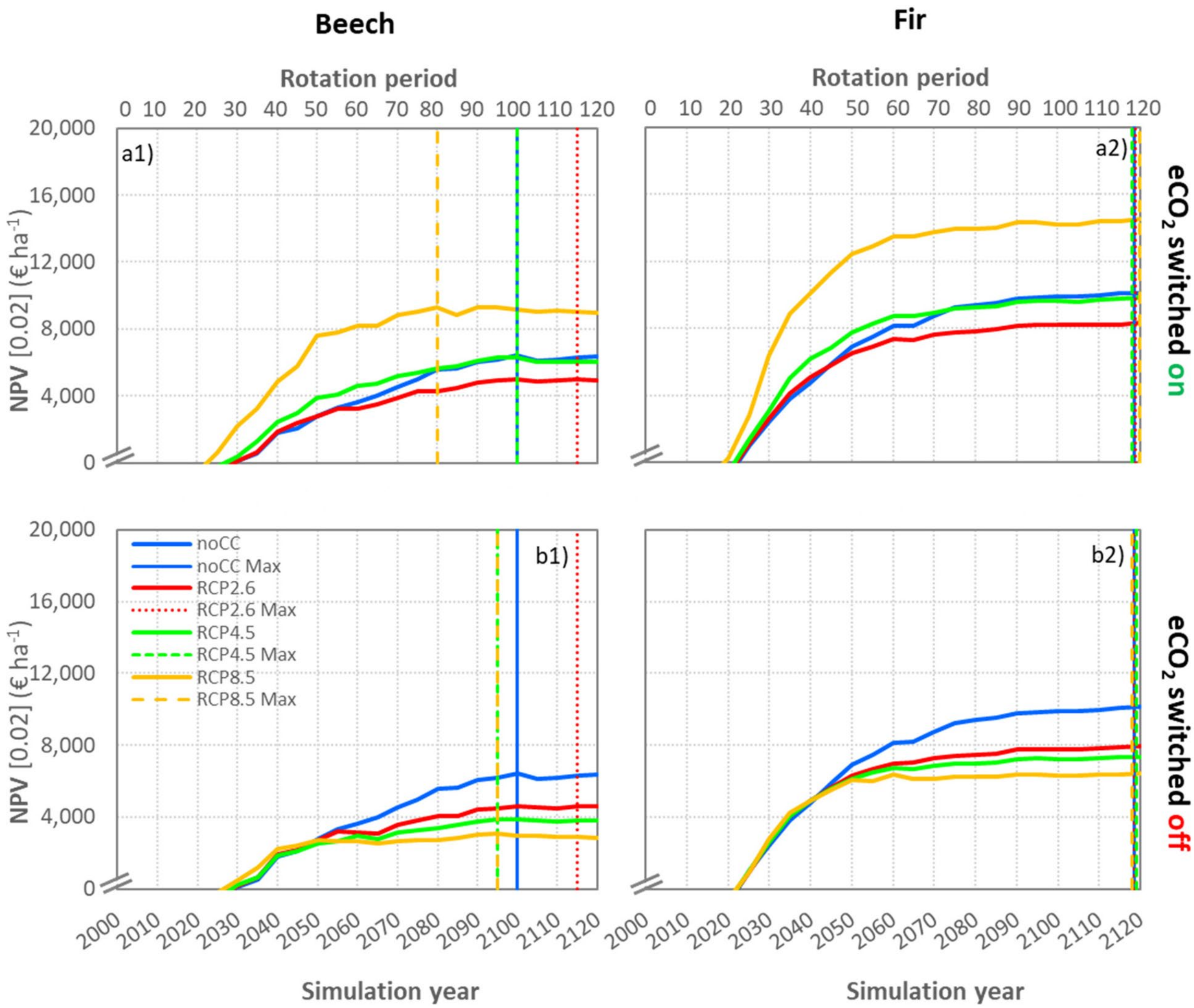

Fig. 20 Evolution of net present value (LEV at $i = 0.02$) under three climate change (CC) scenarios (RCP2.6, RCP4.5, RCP8.5) of beech (1) and fir (2). Simulation year is displayed on the primary *x*-axes (below) and rotation periods on secondary *x*-axes (above). Vertical lines indicate maximum LEV for optimal rotation and final harvest. Simulations started at bare land with natural regeneration (no planting costs) in the year 2000. CC scenarios were run with eCO_2 switched on (**a**) and off (**b**). The control scenario noCC is displayed for comparison. Only positive LEV values are displayed for better visibility

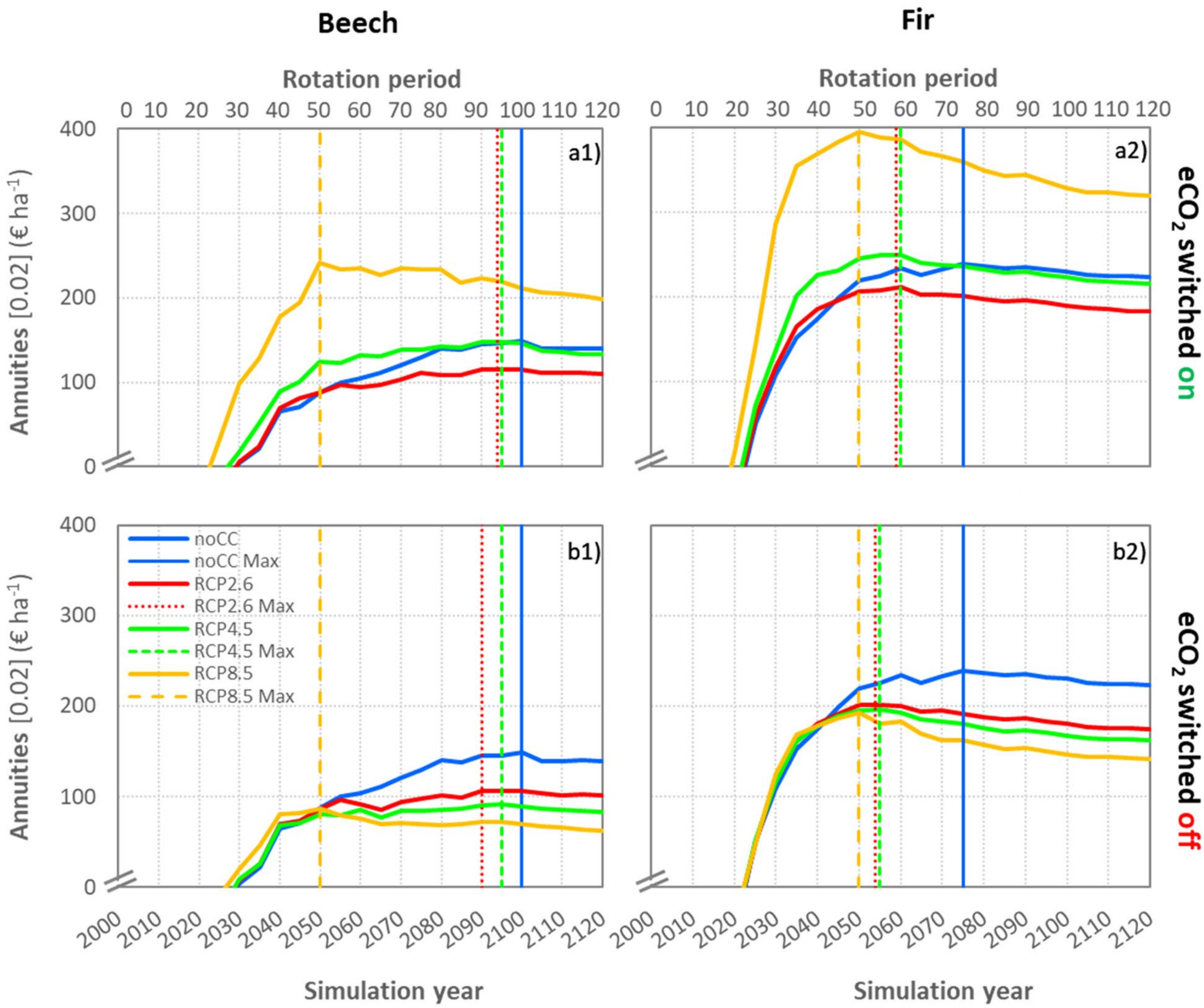

Fig. 21 Effect of climate scenario **a** RCP2.6, **b** RCP4.5 and **c** RCP8.5) on annuities (with 2% interest rate) of beech (1) and fir (2) with eCO_2 switched on combined with 100% photosynthetic downregulation (PD100) and with eCO_2 switched off. The control scenario noCC is displayed for comparison. Inset plot show negative LEV values for better visibility. Vertical lines indicate maximum LEV for optimal rotation. Simulations started with naturally regenerated juvenile stands (no planting costs) (stand age 0)

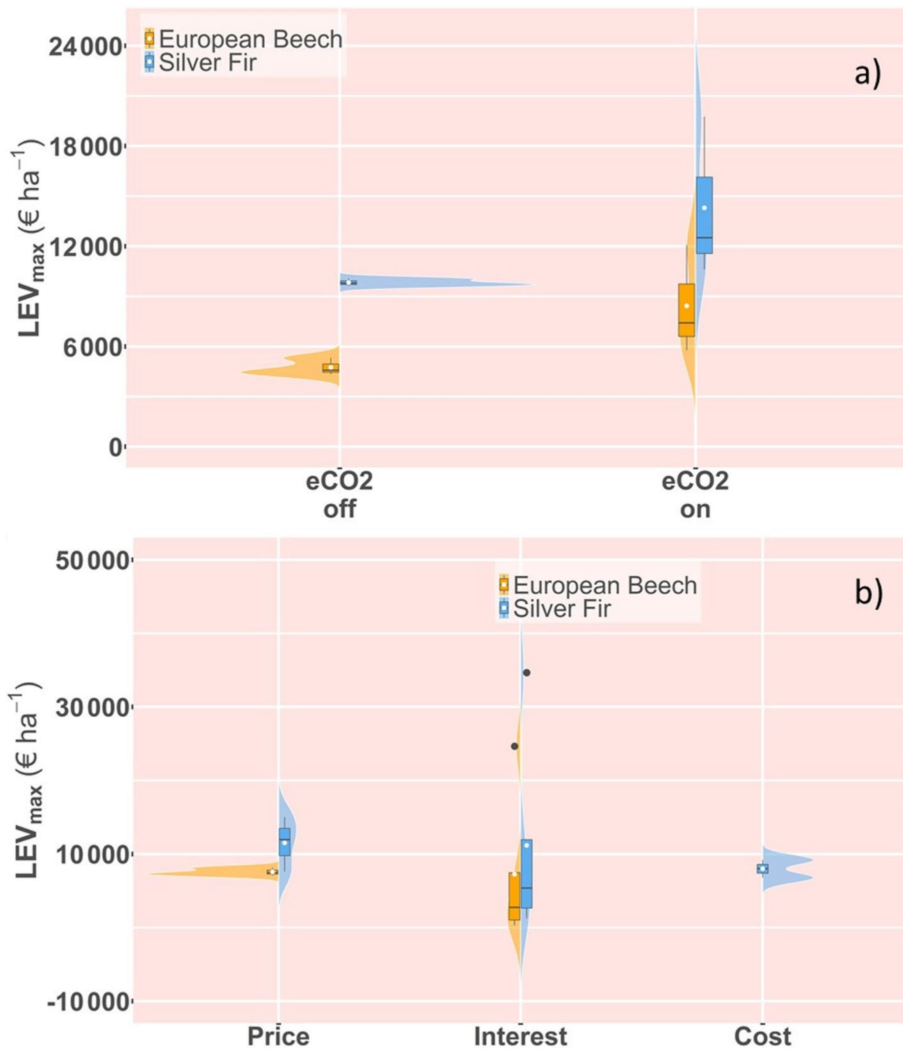

Fig. 22 Split violin plots with boxplots of beech (left) and fir (right) display the uncertainty **a** of the CO_2 fertilization effect within the climate change scenarios RCP2.6, RCP4.5, RCP8.5 with eCO_2 switched on and off and **b** the economic uncertainty stemming from five interest rates (0.01–0.05), fir establishment and protection costs, and timber prices (high and low)

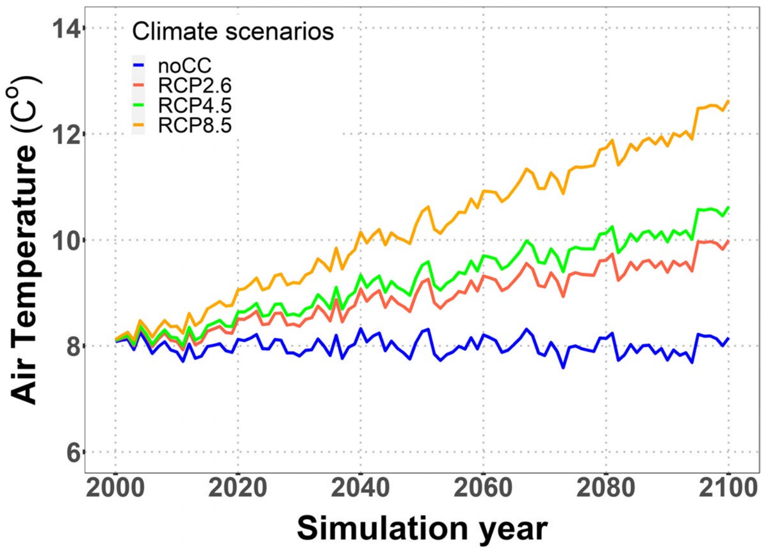

Fig. 23 Development of the mean annual air temperature of three climate scenarios (RCP2.6, RCP4.5 and RCP8.5) and the reference scenario noCC for our study region in the sub-mountainous belt of the Black Forest near Freiamt, Germany (440 m a.s.l., 48° 08.863′ North 7° 54.331′ East)

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Authors' contributions
Conceptualization: DS, RY, MH; Methodology: DS; Formal analysis and investigation: DS; Writing—original draft preparation: DS; Writing—review and editing: RY, MH; Funding acquisition: DS, RY, MH; Resources: DS, RY, MH; Supervision: RY, MH. The authors read and approved the final manuscript.

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Availability of data and materials
The data for the parametrization and calibration of the forest growth simulator are published in (Sperlich et al. 2020)
Tables summarizing the economic results are available in the appendix.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
All authors gave their informed consent to this publication and its content.

Competing interests
The authors declare that they have no competing interests. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results. For transparency, we disclose that co-author Rasoul Yousefpour is associated editor at Annals of Forest Science. He was not involved in review or decision processes.

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