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Effects of Silvicultural Adaptation Measures on Carbon Stock of Austrian Forests

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Abstract: We present the results of a simulation experiment that evaluated three scenarios of forest management in the context of climate change mitigation. Two scenarios refer to climate change adaptation measures. The third scenario was a business-as-usual scenario representing the continuation of current forest management. We wanted to know whether a change in tree species composition or the implementation of shorter rotation cycles is in accordance with the objectives of climate change mitigation. Our simulation experiment was based on data of the Austrian National Forest Inventory. A forest sector simulation model was used to derive timber demand and potential harvesting rates. Forest dynamics were simulated with an individual-tree growth model. We compared carbon stocks, harvesting rates, current annual increment, salvage logging, and forest structure. Compared to the business-as-usual scenario, a change in tree species composition and shorter rotation cycles reduce salvage logging by 14% and 32%, respectively. However, shorter rotation cycles reduce the carbon stock by 27%, but increase the harvesting rate by 4.8% within the simulation period of 140 years. For changes in the tree species composition, the results were the opposite. Here, the carbon stock is increased by 47%, but the harvesting rate is reduced by 15%. Thus, there are clear tradeoffs between the different ecosystem services depending on the climate change adaptation scenario. We also show that a fundamental change in forest management must be accompanied by a transformation in wood processing technology and innovation in wood utilization.

Keywords: climate change adaptation; scenario analysis; growth model; simulation; mixed species stands; carbon sequestration; rotation cycle

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1. Introduction

Austrian forests are currently serving as a sink for greenhouse gas emissions [1] (p. 386). The standing stock of stem wood increased from 280 $m^3 \cdot ha^{-1}$ at the beginning of the 1980s to 351 $m^3 \cdot ha^{-1}$ in 2018 [2]. One reason for this increase is that many of the Austrian forests are comprised of rather young stands (20–40 years) with high growth rates [3]. Furthermore, forest growth has accelerated in past decades because of nitrogen deposition, elevated concentrations of carbon dioxide (CO_2), and longer growing seasons due to global warming [4–7]. In addition, Austrian forest owners have never harvested the full current annual increment (CAI). Within the last three decades, the harvesting rate ranged from 60 to 88% of the CAI [2].

The tree species composition of the Austrian forests is currently dominated by Norway spruce (*Picea abies* [L.] Karst) covering 49.2% of forest area, followed by beech (*Fagus sylvatica* L.) with 10.2%, and other hardwoods such as maple (*Acer pseudoplatanus*) and ash (*Fraxinus excelsior*) with 8.4% [3]. However, within the last century, the growth range of Norway spruce was extended by human activities far beyond its natural growth regions. This extended growth range covers low elevation sites below 600 m a.s.l. mainly located in the lowlands between the Alps and the Danube River and at the eastern edge of the Alps [8]. Growing on such sites, Norway spruce suffers from drought stress, fungi and bark beetle attacks, and storm damage. As a consequence of the heavy storm events Vivian and Wiebke in 1990, forest owners started to convert these secondary Norway spruce stands into mixed species stands comprised of beech, oak, maple, and ash. Additionally, shorter rotation cycles were discussed for the remaining young stands of Norway spruce. This discussion was based on the observations that the risk of storm damage increases with increasing stand age and stand height [9–11].

The establishment of mixed species stands and the implementation of shorter rotation cycles are perceived to be silvicultural measures to adapt Austrian forests to climate change [12–15]. They are completely in line with the second objective of "Climate Smart Forestry" (CSF) that "*builds upon three main objectives; (i) reducing and/or removing greenhouse gas emissions; (ii) adapting and building forest resilience to climate change; and (iii) sustainably increasing forest productivity and incomes*" [16]. What may be overlooked is that there may be some tradeoffs between the different objectives; for example, silvicultural adaptation measures for building forest resilience to climate change may remain in conflict with measures of climate change mitigation and/or increasing productivity [15,17].

In this paper, we tried to determine whether there are some tradeoffs between carbon storage, productivity, and enhanced forest resilience to climate change. We present the results of a simulation experiment that evaluated three scenarios of forest management in the context of climate change mitigation. Specifically, we wanted to analyze the effects of a changing tree species composition and shorter rotation cycles on the development of carbon stocks of Austrian forests. These two scenarios refer to climate change adaptation measures and were derived from ongoing discussions among forest owners and forest managers, and from stakeholder interviews [18]. Both scenarios were compared to a business-as-usual scenario that represented the continuation of current forestry management practices. A similar study was previously presented by Seidl et al. [19], who used a private forest management unit in southern Austria as a case study. However, our simulation experiment goes beyond the local level and is based on a national scale using the data of the Austrian National Forest Inventory (ANFI). We compared the total carbon stock of Austrian forests until 2150. Additionally, we analyzed the development of harvesting rates, CAI, salvage logging, and forest structure.

2. Materials and Methods

2.1. Data of the Austrian National Forest Inventory (ANFI)

Initial data for setting up our simulation experiment were provided by the sample plots of the ANFI assessed during the period from 2007 to 2009. The sample plots cover the whole Austrian territory regularly distributed by a 3.89 × 3.89 km sampling grid. These plots are clustered into tracts, each comprised of four plots that are arranged in a square of 200 × 200 m. To avoid research plot bias [20], a hidden plot design was used. Each sample plot consists of two concentric circles with fixed radii of 9.77 and 2.6 m, respectively, and a Bitterlich sample [21] using a basal area factor of 4 $m^2 \cdot ha^{-1}$. Site characteristics, which were required to run the forest growth model, were assessed on the fixed plot with 9.77 m radius. Individual-tree data were collected on the smaller fixed plot for trees with a diameter at breast height (DBH, 1.3 m) between 5.0 and 10.4 cm, and via Bitterlich sampling for trees with a DBH larger than 10.4 cm. Tree species, DBH, tree height (H), and height of the crown base (HCB) were recorded for all sample trees.

The ANFI comprises a total of 22,000 sample plots; approximately 11,000 plots are at least partially covered by forest area. In this paper we restricted ourselves to 7964 sample plots that are characterized by a share of at least 7/10 in forest land. This restriction was necessary because the applied forest growth model (see Section 2.3) is not able to handle sample plots with a lower share in forest land. These 7964 sample plots represent a total of 3.367 million hectares of managed forest land.

2.2. Scenarios of Forest Management

2.2.1. Business-as-Usual (BAU)

We assumed that further demand for wood in terms of volume and timber assortments will follow the same market framework conditions as observed in the recent two decades. Production of sawn wood, boards, paper, and fuel wood will follow market conditions (income and price elasticities derived from time series considering the time period 1965–2015). The behavior of market players was assumed to be unchanged over time; this means, e.g., no radical innovation is considered; future market conditions such as elasticities for demand and supply, and cross-price elasticities, do not change in the future; and timber from broadleaved trees cannot be used as a substitute for timber from coniferous trees for all assortments. The importation of timber, recycling paper, and fuel wood was dependent on market rules. Note that we did not assume any improvements in wood processing technology and innovations in product lines. Thinning and tending were performed according to stem number guidelines (Figure 1). Final harvesting was preferably carried out on the plots with the highest revenues net of costs, i.e., mainly on easily accessible sites with low costs of harvesting. Harvested plots were replanted with those tree species that had already been present on the respective plots.

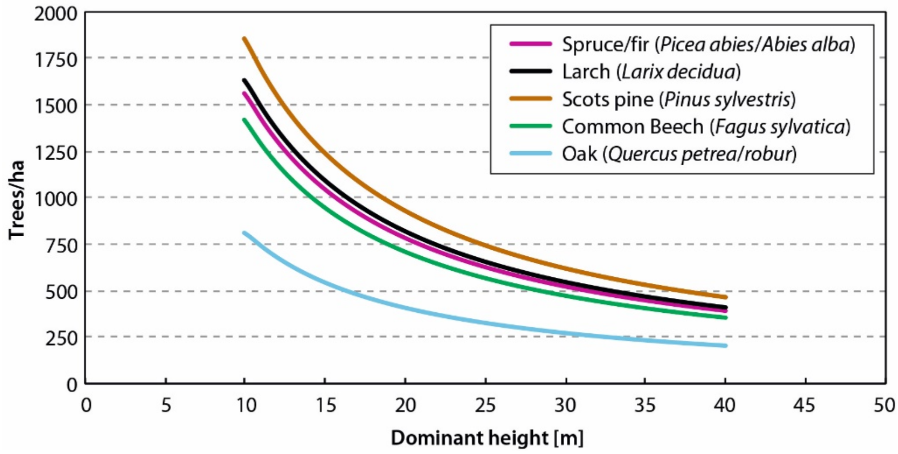

Figure 1. Stem number guidelines used for thinning and tending in the simulation.

2.2.2. Change in Tree Species Composition (CSC)

From an economic point of view, this management scenario was identical to the BAU scenario. Moreover, thinning, tending, and final harvesting were carried out analogously to the BAU scenario. However, the main difference to the BAU scenario was the way in which the harvested plots were replanted with new trees. For each plot where a final harvest had been conducted, the expected mean temperature 50 years after final felling was derived from the applied climate scenario (see Section 2.4). Based on the expected mean temperature, the selection of the tree species was undertaken according to a specific protocol (Table 1). However, tree species selection was also based on soil type and vegetation type, which both characterize soil moisture. Plots with conifers were replanted with 2500 trees$\cdot$ha^{-1}; plots with broadleaved trees with 4000 trees$\cdot$ha^{-1}. In case the protocol specified more than one tree species per plot, a mixed stand was replanted by randomly selecting from the allowed tree species.

Table 1. Tree species selection for replanting harvested plots in the CSC scenario. (Mean temperatures according to Mayer [22]).

Mean Temperature	Tree Species
<6 °C	Conifers (*Picea abies, Abies alba, Larix decidua, Pinus sylvetris*)
6–7 °C	Conifers, Maple (*Acer pseudoplatanus*)
7–8 °C	Conifers, Maple, Beech (*Fagus sylvatica*)
8–11 °C	Maple, Beech, Oak (*Quercus petrea/robur*)
11–12 °C	Maple, Oak
>12 °C	Oak

2.2.3. Shorter Rotation Cycles (SRC)

The general economic assumptions, and the guidelines for thinning and tending, were identical to those of the BAU scenario. Moreover, harvested plots were replanted with those tree species that had already been present on the respective plots. The main difference between BAU and SRC referred to the determination of the final harvesting amount. In both the BAU and the CSC scenario, we followed a demand-driven approach where the final harvesting amount was calculated by a forest sector model and transferred to a forest growth model (see Section 2.3). In the SRC scenario it was the opposite. Here, the final harvesting amount was the result of management measures specified in the forest growth model. The objective of these management measures was to decrease the mean age at final felling from 100 to 75 years in order to reduce the susceptibility to windthrow. Because the implementation of the SRC scenario is based on clear fellings, it could not be implemented in set-aside areas, in the fringe of set-aside areas, and in protective forests. Therefore, the SCR scenario could only be applied to 2.592 million hectares of forest land. To determine the annual allowable cut, the 2.592 million hectares were divided by 75. The result of 34,560 ha comprised the annually harvestable area on which the annual final fellings were carried out. The starting point for the annual final fellings was always the plot with the highest stand volume per hectare.

2.3. Model Ensemble Used for Scenario Analysis

We used an ensemble of three models to simulate the carbon stocks in the Austrian forests. For this purpose, the individual-tree based forest growth model CALDIS [23] was linked to the soil carbon model YASSO15 [24–26] and to the forest sector simulation model FOHOW2 (Forst- und Holzwirtschaft Version 2). FOHOW2 is based upon FOHOW [27,28], but uses a wider range of assortments and updated information about market conditions in Austria [29]. The mutual dependency between these models allowed us to simulate interactions between forest growth, the wood product chain, and soil carbon [29].

CALDIS is a distance-independent, individual-tree-based forest growth model that resorts to the model concepts of PROGNAUS [30,31] and PROGNOSIS [32]. Usually, individual-tree based forest growth models comprise a set of species-specific functions for growth, mortality, and regeneration. These functions are used to predict the growth of all individual trees standing on a plot. Stand characteristics are obtained by aggregating individual tree values. Because of their high flexibility, individual-tree based forest growth models can simulate forest stands of any composition, from pure even-aged to mixed-species uneven-aged [31]. CALDIS is comprised of a basal area increment model [33] and a height increment model [34], which are both sensitive to climate variables. CALDIS also contains an ingrowth model for estimating the number of those trees that exceed the 5 cm DBH threshold [35], and it contains models to estimate competition-induced mortality and salvage logging caused by windthrow, drought, and bark beetle attacks. The model for estimating salvage logging is a probabilistic model (LOGIT function) that was parameterized from ANFI data covering the time period from 1981 to 2002. It predicts the probability of salvage logging depending on stand and site characteristics, and wind speed, temperature, and precipitation [9].

FOHOW2 is a partial equilibrium [36] dynamic forest sector simulation model developed for Austria's wood product chain. It is mainly used to explore long-term development of the Austrian forest sector [37–40]. FOHOW2 is split up into two sub-models comprising eight modules in total. The most important modules used in this analysis are:

1. General economy;
2. Forest product markets;
3. Timber supply from Austrian forests;
4. Round wood markets defined as interactions between the modules "Timber supply from Austrian forests" and "Forest product markets";
5. Forest resources in terms of forest area, growing stock, and CAI;

A more detailed description of the FOHOW2 model can be found in Schwarzbauer and Rametsteiner [28], and Schwarzbauer and Stern [37].

YASSO15 is a model for simulating soil carbon stocks [24–26]. The core module of YASSO15 is a model where organic matter is decomposed to CO_2 and soil organic matter as a result of respiration. The output of YASSO15 is the total soil carbon stock and its two parts, i.e., wood and non-woody soil organic matter. It is driven by climatic conditions and the aboveground and belowground litter fall provided by CALDIS.

2.4. Climate Data

To run CALDIS and YASSO15 we used regionalized climate projection data from the ÖKS15 database [41]. These climate data were downscaled to all plots of the ANFI. The objective of our simulation experiment was to analyze the effects of silvicultural measures on carbon stocks. To extract the pure effect of a treatment in an experiment, it is important to control for all other factors. Therefore, we decided to use only one climate scenario to avoid confounding between silvicultural treatments and climate. We resorted to the RCP 8.5 pathway, which indicates an increase in the mean annual temperature until the end of the century of ~4.8° Celsius compared to the year 2000. However, the RCP 8.5 pathway shows no temporal change for the projected annual precipitation. Because we wanted to simulate the full development of newly established stands, the climate data provided by ÖKS15 were extended until 2150. For the mean annual temperature, the LOGISTIC-function was fitted to the data from 1971 to 2100. Model coefficients were estimated by non-linear regression. To predict the mean temperature for a year beyond 2100, we used the value of a randomly selected year between 2070 and 2100, subtracted the model estimate of the respective year, and added the model estimate of the year for which the prediction had to be undertaken. For the extrapolation of the annual precipitation data, no temporal trend was assumed. Thus, the values were randomly selected from the years between 2070 and 2100. In the year 2150, the mean annual temperature was 14.6 °C, and the mean annual precipitation was 1396 mm. The results are shown in Figure 2.

2.5. Simulation Protocol

The simulation runs for both the BAU and the CSC scenarios were started by FOHOW2, which modeled timber prices and potential harvesting amounts for conifers and broadleaved trees. The harvesting amount of conifers was further stratified according to ownership (small private owners (<200 ha), large private owners (>200 ha), federal forests), and age-class (younger or older than 60 years). Harvesting amounts and timber prices were then transferred to CALDIS, where tree selection for potential harvest was undertaken as follows:

- No harvesting in set-aside areas (e.g., core zones of national parks);
- In the fringe of set-aside areas and in protective forests only single tree selection was allowed for final felling (no clear felling), and tree selection started with the largest trees;

- Thinning and tending in stands younger than 60 years was based on stem number guidelines, and trees for removal were randomly selected;
- According to the Austrian forest act, crown closure after thinning, tending, or single tree selection had to be at least 0.6;

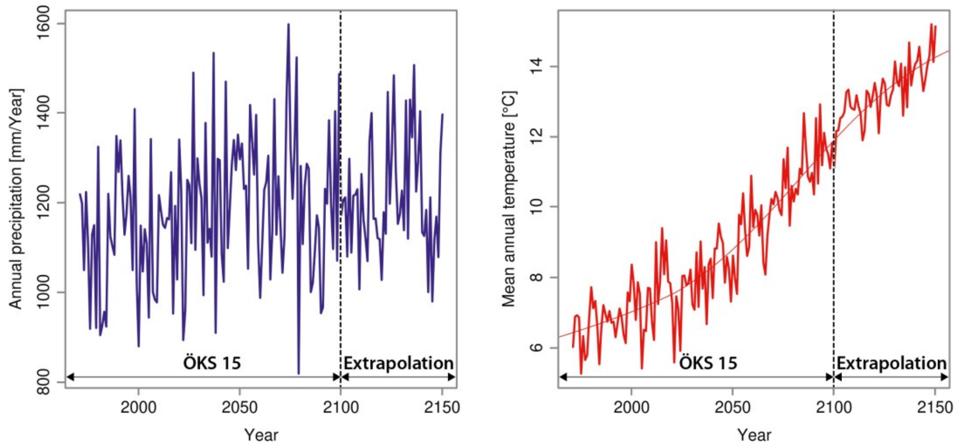

Figure 2. Annual precipitation and mean temperature in Austria according to the RCP 8.5 pathway. The data were downloaded from the ÖKS15 database [41] and extrapolated to the year 2150.

After marking the trees for potential harvest, a plot-wise calculation of the revenues net of costs was performed on the basis of the timber prices delivered by FOHOW2. Costs for harvesting were estimated according to the applied harvesting system, in addition to site characteristics such as slope and distance to the nearest (forest) road. Subsequently, all ANFI plots were sorted by the revenues net of costs in descending order. Removal of individual trees was started on the plot with the highest revenue net of costs, and was continued until the potential harvesting amount was reached. When the harvesting was finished, the increment of the remaining trees was estimated and the clear-felled plots were replanted with the designated tree species (see Section 2.2). After updating the stand characteristics, the actual harvesting amount, growing stock, and CAI were transferred back to FOHOW2, which used this updated information to start the calculations for the subsequent year.

In the SRC scenario, the simulation procedure was slightly different from those of the BAU and CSC scenarios. Here we started the simulation runs with the harvesting module in CALDIS. In the SRC scenario, the annual cut was determined by a numerically fixed forest area and not a demand-driven annually changing amount of wood volume estimated by FOHOW2. Therefore, the ANFI plots were sorted by stand volume in descending order. Removal of individual trees was started on the plot with the highest stand volume per hectare and continued until 34,560 ha of forest area was reached (see Section 2.2.3). The general procedure for tree selection for potential harvest was the same as that in the BAU and CSC scenarios. As described for the BAU and the CSC scenarios, actual harvesting amount, growing stock, and CAI were transferred back to FOHOW2 for further calculations. The implementation of reducing the rotation cycles in the SRC scenario started in the year 2025.

All three scenarios of forest management were simulated in annual steps for a period of 140 years. Such a long simulation period was intentionally chosen because we wanted to see the full development of newly established stands and—especially in the CSC scenario—the reaction of the timber market to a substantially modified tree species composition.

2.6. Calculation of Carbon Stock

The carbon stock of Austrian forests was calculated as the sum of the carbon stock of the above and belowground biomass of living trees (CSL), the carbon stock of the stem biomass of standing dead trees (CSD), and the soil carbon stock (SCS). CSL and CSD were calculated as:

$$CSL = \sum \left(V_S \cdot \left(1 - \frac{\beta}{100} \right) \cdot \rho + BNDM + RDM \right) \cdot EF \cdot f_C \quad (1)$$

$$CSD = \sum V_S \cdot \left(1 - \frac{\beta}{100} \right) \cdot \rho \cdot EF \cdot f_C \quad (2)$$

where:

CSL, CSD = respective carbon stock in megatons (Mt = 10^9 kg)
V_S = solid tree volume of a sample tree (m^3)
β = shrinkage factor (%)
ρ = wood density (oven dry mass over oven dry volume; Mt/m^3)
$BNDM$ = branch and needle dry matter of a sample tree (Mt)
RDM = root dry matter of a sample tree (Mt)
EF = expansion factor of a sample tree for scaling up to total forest area
f_C = carbon fraction of biomass dry matter (0.5)

Stem volume was converted to stem mass with tree species-specific wood densities and shrinkage factors [42]. The tree species-specific equations for the mass of branches, needles and leaves, and total roots were derived from Austrian experiments and are completely referenced in Weiss [43]. The mass of fine roots (<2 mm) was chosen to be 5% of the total root biomass [44,45]. SCS was simulated with YASSO15, where the influx of organic carbon was estimated from input parameters provided by CALDIS. The annual flux of organic carbon from the respective biomass compartments by litterfall (including branch, needle, and root dry matter of standing dead trees), mortality, and harvest residues to the soil was estimated by assigning each biomass compartment a certain turnover rate. The assumptions on the turnover rates were based on observations from intensive monitoring plots and from literature information, as previously described [46,47].

2.7. Analyses

The three abovementioned scenarios of forest management were compared with regard to the total carbon stock of the Austrian forests. In order to determine whether there are some tradeoffs between carbon storage, productivity, and enhanced forest resilience to climate change, we analyzed the development of harvesting rates, CAI, and the amount of salvage logging. Silvicultural adaption measures are also expected to have an impact on the development of forest structure. To gain some insights into the changes in forest structure, we also analyzed tree species composition and age-class distribution.

3. Results

3.1. Development of Carbon Stock in Austrian Forests

The carbon stocks of all three management scenarios started from an initial value of 357 Mt C in 2010 and increased continuously. However, the length of the period with increasing carbon stocks differed substantially between the management scenarios. In the BAU scenario, the carbon stock increased until 2075, and entered a phase with a decreasing carbon stock afterwards. In the SRC scenario, the phase of increasing carbon stock was much shorter and ended in the year 2025; then, the carbon stock decreased continuously until the end of the simulation period in the year 2150. By comparison, the CSC scenario maintained a similar carbon stock as that of the BAU scenario until 2075. However, in contrast to the BAU scenario, the carbon stock in the CSC scenario was more or less stable until the year 2110, and increased again until the end of the simulation period. Thus, in the year 2150, the highest carbon stock was reached in the CSC scenario, of 452 Mt, followed by the BAU scenario with 307 Mt, and the SRC scenario with a value of 223 Mt (Figure 3). Forests serve as carbon sinks, if their carbon stocks increase. However, forests become a carbon source if their carbon stocks decrease. In the BAU scenario of our simulation experiment, Austrian forests serve as a carbon sink until 2070 and become a carbon source afterwards. In the SRC scenario, the phase in which the Austrian forests are a carbon sink is much shorter and ends in the year 2025. After 2025, Austrian forests are a significant carbon source. In the CSC scenario, Austrian forests serve as a carbon sink until 2080, become a carbon source until 2110, and finally return to being a carbon sink. At the end of the simulation period, Austrian forests are more or less carbon neutral in the CSC scenario, i.e., they are neither a carbon sink nor a carbon source (Figure 3).

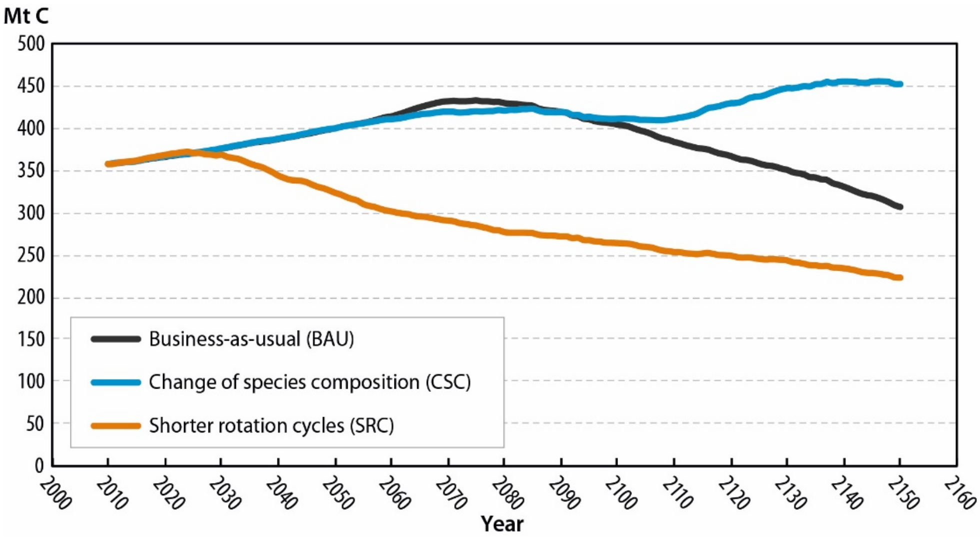

Figure 3. Carbon stock of Austrian forests in three forest management scenarios.

3.2. Annual Harvesting Rates

Figure 4 displays the annual harvesting rates for the three different forest management scenarios. Note that harvesting rates refer to harvested log volume under bark. From 2010 to 2025, the annual harvesting rates were almost identical for all three scenarios. Beyond 2025, the BAU scenario showed an annual harvesting rate of approximately 20 million m^3 per year. Considering the time frame from 2010 to 2100, the annual harvesting rate of the CSC scenario was rather similar to the annual harvesting rate of the BAU scenario. However, from 2100 to 2120, the annual harvesting rate of the CSC scenario decreased rapidly from 20 million m^3 per year to only 11 million m^3 per year. Rather different was the situation for the SRC scenario. Here, the annual harvesting rate increased sharply in the year 2025. This can be explained by the simulation protocol because the implementation of reducing the rotation cycles in the SRC scenario to reduce the risk of windthrows and the related preferred harvest of older stands started in 2025. Then, for a period of more than 50 years, the annual harvesting rate of the SRC scenario was at least 25% higher than the annual harvesting rate of the BAU scenario. The harvesting rate of the SRC scenario did not fall below the harvesting rate of the BAU scenario until 2080, finally reaching a level of approximately 15 million m^3 per year. Considering the entire simulation period, the total harvesting amount was 2848 million m^3 in the BAU scenario, 2425 million m^3 in the CSC scenario, and 2985 million m^3 in the SRC scenario. Hence, the total harvesting amount in the SRC scenario was 4.8% higher than that in the BAU scenario. In contrast, the total harvesting amount in the CSC scenario was 14.9% lower than that in the BAU scenario.

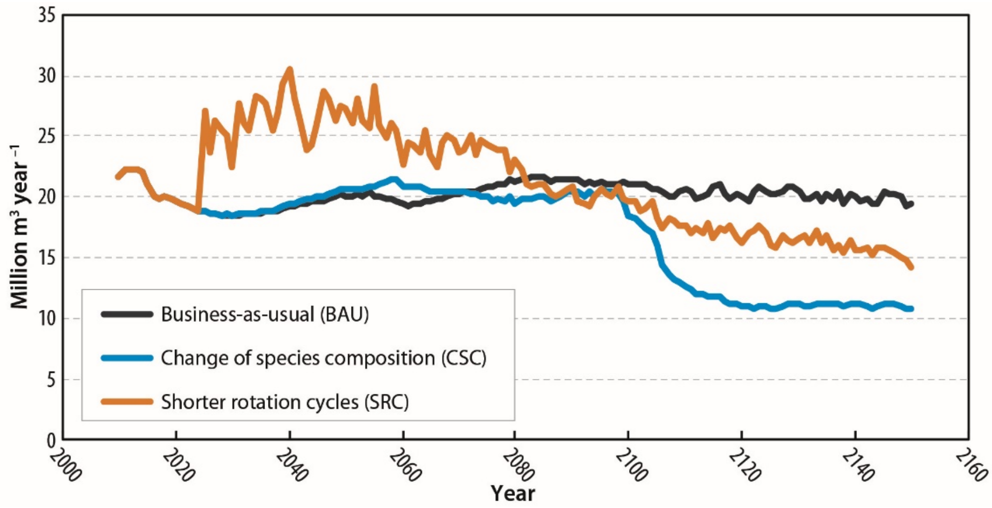

Figure 4. Annual harvesting rates of three forest management scenarios (log volume under bark).

Figures 5 and 6 show the annual harvesting rates of all three management scenarios split for conifers and broadleaved trees. Here it becomes obvious that the overall harvesting rates (Figure 4) are mainly driven by conifers (Figure 5). Although the annual harvesting rate of broadleaved tree species increases in scenario CSC over the entire simulation period (Figure 6), the loss in the harvesting rate of conifers cannot be compensated by the gain in the harvesting rate of broadleaved tree species.

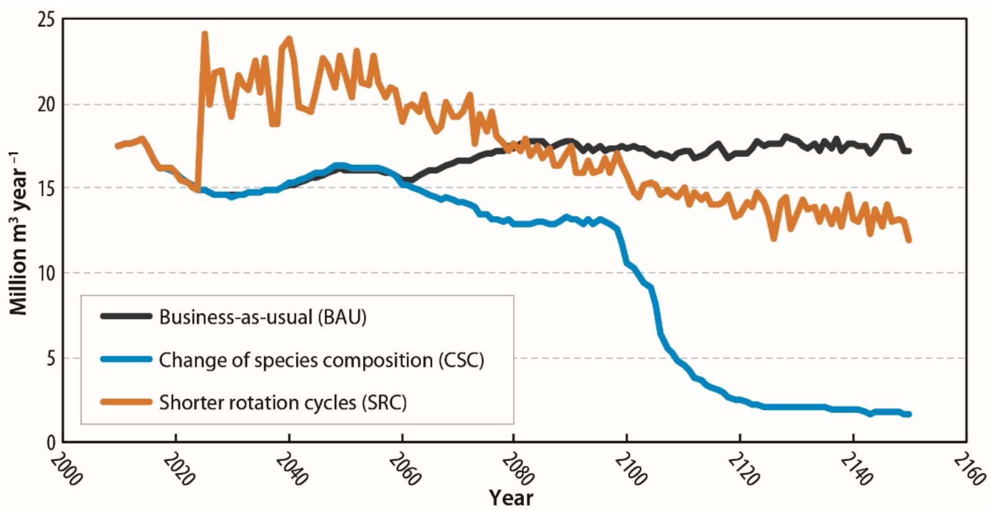

Figure 5. Annual harvesting rates of conifers of three forest management scenarios (log volume under bark).

3.3. Current Annual Increment (CAI)

The CAI of all three management scenarios started from an initial value of 33.6 million $m^3 \cdot year^{-1}$ in 2010 and decreased over the entire simulation period. Referring to the time period from 2010 to 2035, the CAI was more or less identical for all three scenarios. Beyond 2035, the SRC scenario always showed the lowest CAI. Regarding the BAU und CSC scenarios, the situation was somewhat different. In the time period from 2035 to 2090, the BAU scenario showed the highest values of CAI, followed by the CSC scenario. However, this ranking changed beyond 2090, where the situation was the opposite, and the CSC scenario showed slightly higher values of CAI than the BAU scenario (Figure 7).

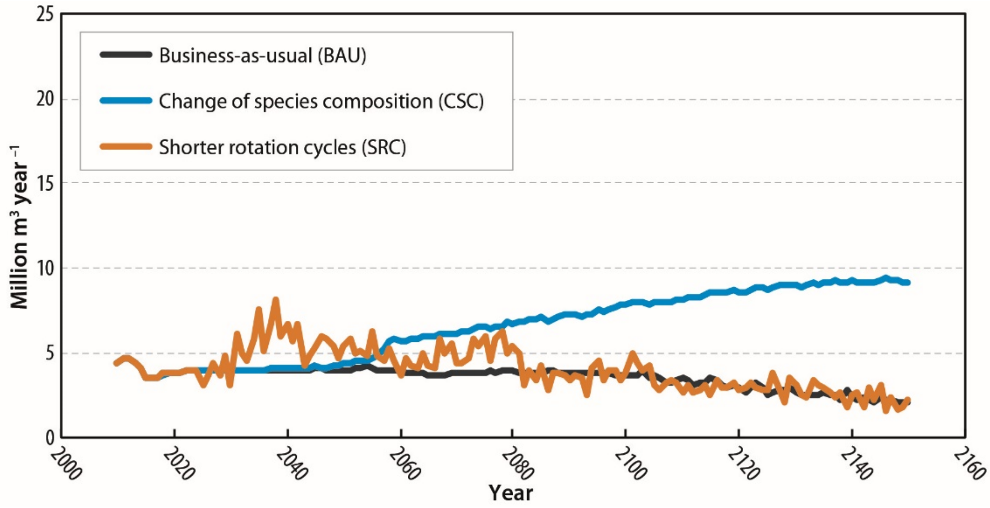

Figure 6. Annual harvesting rates of broadleaved trees of three forest management scenarios (log volume under bark).

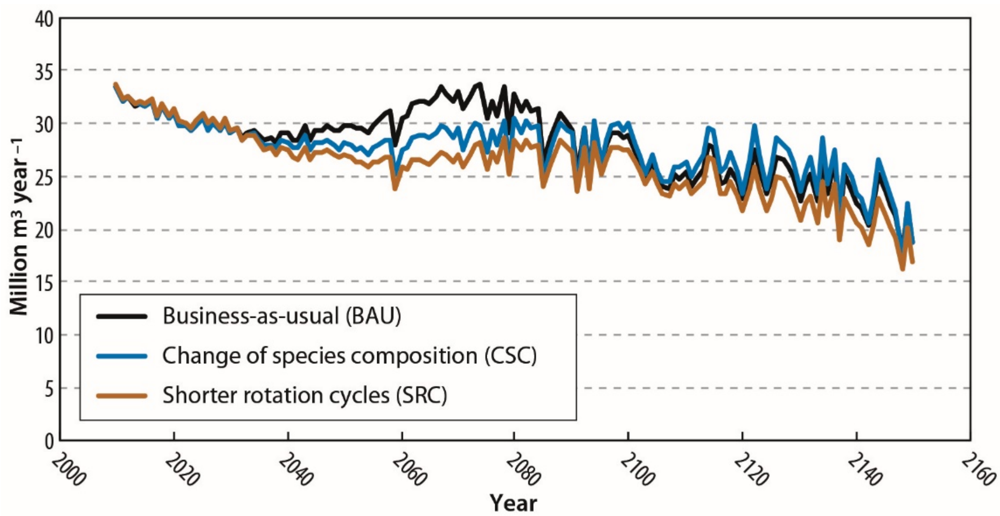

Figure 7. Current annual increment (tree volume over bark) of three forest management scenarios.

3.4. Salvage Logging caused by Wind, Snow, and Bark Beetles

The total amount of salvage logging was 189 million m^3 over bark for the BAU scenario, 162 million m^3 over bark for the CSC scenario, and 129 million m^3 over bark for the SRC scenario. Thus, salvage logging of the CSC scenario was 14% lower, and salvage logging of the SRC scenario was 32% lower, than the salvage loggings of the BAU scenario (Figure 8).

3.5. Forest Structure

Table 2 displays the tree species distribution for the initial status in the year 2010 and for the different management scenarios at the end of the simulation period in the year 2150. Here it can be seen that the proportions of conifers and broadleaved trees remained more or less unchanged in the BAU and the SRC scenarios, but were clearly different in the CSC scenario.

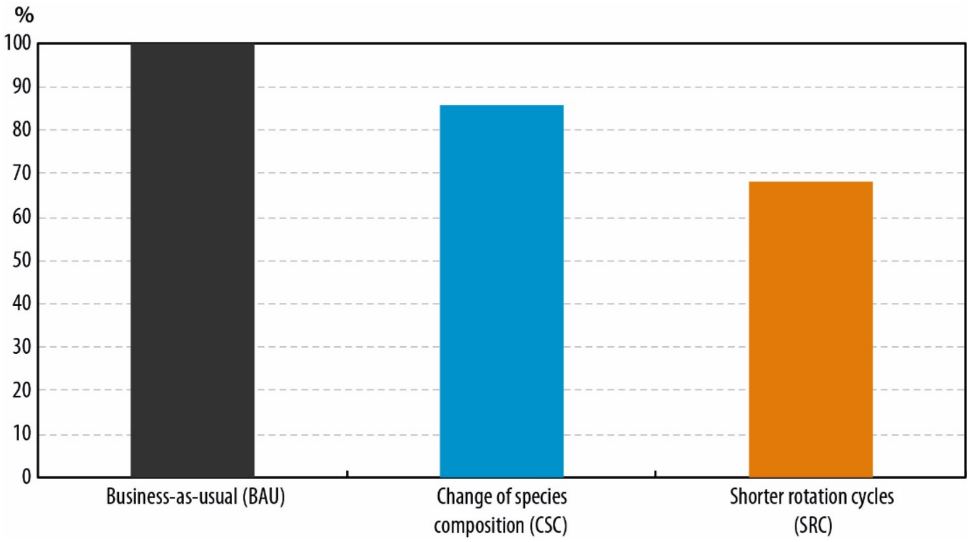

Figure 8. Comparison of salvage logging of three forest management scenarios.

Table 2. Tree species distribution by stand basal area (%).

Scenario/Year	Conifers	Broadleaved Trees
Status 2010	78	22
Business-as-usual (BAU) 2150	78	22
Change in species composition (CSC) 2150	26	74
Shorter rotation cycles (SRC) 2150	79	21

Figure 9 shows the changes in the age-class distributions of the three management scenarios compared to the initial situation in the year 2010. All management scenarios showed an increase in forest area in the age-class 0–20 years, which is most pronounced for the SRC scenario, followed by the BAU and the CSC scenarios. In the age-classes 20–40 and 40–60 years, the BAU and SRC scenarios showed an increase in forest area, whereas the CSC scenario led to a slight decrease. All other age-classes, except for age-class 140+, showed a decrease in forest area in all management scenarios. This decrease was most pronounced for the BAU and the SRC scenarios, and less pronounced for the CSC scenario. In age-class 140+, the results are similar to those of age-class 0–20 years, because a sharp increase in forest area can be observed for all three management scenarios.

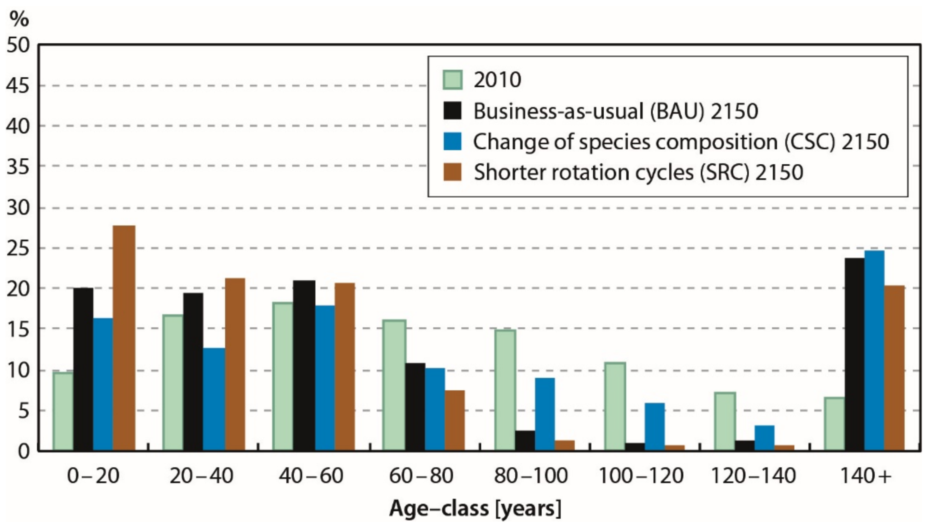

Figure 9. Change in age-class distribution of three forest management scenarios. The Y-axis displays the percent-share of total forest area.

4. Discussion and Conclusions

Increasing forest resilience to climate change is one of the main objectives of silvicultural adaptation measures. By applying these measures, forest stands should become less susceptible to storm damage, dry spells, and bark beetle attacks. A lower susceptibility to disturbances should also result in a lower amount of salvage logging. These expectations are clearly supported by the results of our simulation experiment. Replacing Norway spruce by better adapted broadleaved tree species reduced the amount of salvage logging by 14%. An even stronger effect was observed for the SRC scenario, where the mean age at final felling was decreased from 100 to 75 years. Here the amount of salvage logging was 32% lower compared to the BAU scenario. Thus, the evaluation of the two silvicultural adaptation measures shows that both are able to substantially reduce susceptibility to climate change. In this regard, our results are in line with Seidl et al. [15].

Considering the development of carbon stock and productivity, the results for the SRC scenario are unambiguous. In the SRC scenario, the carbon stock at the end of the simulation period was 27% lower compared to the BAU scenario, and the productivity in terms of cumulated increment was 7% lower. Thus, reducing the length of the rotation cycles leads to a tremendous loss in stored carbon and to a reduction in productivity in terms of CAI. The positive effects of reduced susceptibility to disturbances are accompanied by the negative effects of lowered carbon storage and productivity.

Although the total harvesting amount in the SRC scenario was 4.8% higher than in the BAU scenario, the SRC scenario is not a scenario of intensified forest management. Such a scenario would not simply reduce the length of the rotation cycles as was done in our simulation experiment; rather, it would search for various measures to increase forest productivity. A scenario of intensified forest management would therefore resort to improved techniques of tree regeneration, fast growing tree species, and rotation cycles that provide maximum growth. Moreover, it would foster all measures that are able to produce high-quality timber, e.g., artificial pruning. In our simulation experiment, shorter rotation cycles were only used to prevent forest owners from undertaking large amounts of salvage logging.

With regard to carbon stock, the CSC scenario shows a rather different result. At the end of the simulation period, the carbon stock of the CSC scenario is 47% higher compared to that of the BAU scenario. However, this is far less the effect of the silvicultural treatment, and depends on our modeling assumptions in the forest sector simulation model FOHOW2. Here we kept the current status with a strict focus on conifers, specifically on Norway spruce. No improvements in wood processing technology and innovations in product lines were assumed, and the development of wood demand of the forest sector was kept constant at today's level. Conifers are mainly used for producing long-lived products, whereas broadleaved trees are preferably used as fuel wood. As a consequence, the modeled demand for conifers was still high in the CSC scenario, and the harvesting rates in the CALDIS model were maintained at the harvesting rates of conifers in the BAU scenario. This was possible until the year 2060 (Figure 5). Thereafter, there was a slight decrease in the harvesting rates of conifers, which could almost be compensated by the increased harvesting rates of broadleaved trees. However, around the year 2100, there was a sharp drop-off in the harvesting rates of conifers that could not be offset by broadleaved trees (Figures 4–6). The increased carbon stock at the end of the simulation period is therefore the result of reduced harvesting rates caused by the inherent modeling assumption that coniferous timber can only partially be substituted by the timber of broadleaved trees. Consequently, the change in the species composition of the forests, and the stable demand of wood species and assortments, are the reasons for the increase in the carbon stock in the CSC scenario, because the broadleaved trees are less requested by the wood industry than the conifers.

The interpretation of the CAI development is rather complex since there are many factors that either intensify or weaken an observed trend. One of these crucial factors is the climate. In Austria, we assume that CAI will increase at high-elevation sites, as long as there are no counterproductive climate change effects from natural disturbances, but will decrease in the lowlands [48]. Therefore, the effects of climate change may confound, for instance, the well-known age-dependent decrease in CAI. Another important issue in this context is that CAI development can also be affected by harvesting rates and a changing tree species composition. To explain this, let us refer to the development of CAI of the BAU and CSC scenarios (Figure 7). We know from our yield tables that, in terms of volume growth, stands of broadleaved trees are less productive than stands of conifers [49]. Thus, one may expect a lower CAI when former coniferous stands are successively replaced by stands of broadleaved trees. In our simulation experiment, this expectation is met during the time period from 2035 to 2090, where the CSC scenario shows a lower CAI than the BAU scenario. However, beyond 2100, the situation is the opposite, and the CSC scenario shows a higher CAI than the BAU scenario. This change in the ranking of the scenarios can be attributed to the decrease in harvesting rates in the CSC scenario beyond 2100 (Figure 4).

Forest structure influences the productivity, protective function, and recreational value of a forest, i.e., they depend on tree species composition and age-class distribution, among other factors. Our results show that there was almost no change in tree species composition in the BAU and SRC scenarios. By comparison, the tree species composition was completely reversed in the CSC scenario (Table 2). These results were not unexpected due to the specification of the management scenarios. However, if forest owners in Austria further promote the shift from coniferous to broadleaved forests, we have to expect a decrease in productivity in terms of volume growth. Our simulation experiment further showed that Austrian forests became younger. This is especially true for the SRC scenario, but also for the BAU scenario. In all three scenarios of forest management, we could observe an increase in forest area in the age-classes below 60 years, and a decrease in forest area in the age-classes between 60 and 140 years. However, most conspicuous, although not surprising, is the sharp increase in forest area in age-class 140+ (Figure 9). The reason for this increase can be found in the simulation protocol. No harvesting was allowed in set-aside areas, and only single tree harvesting was allowed in the fringe of set-aside areas and in protective forests. Over the entire simulation period of 140 years, these specifications lead to forests with a continuous crown cover comprised of old trees. Young trees are rare because of the low ability for natural regeneration due to unfavorable site conditions and a high browsing impact. In Austria, such stands are often found in protective forests [50].

All simulation runs lead to plausible results. The CSC and the SRC scenarios reduce salvage logging compared to the BAU scenario. However, the increase in the carbon stock in the CSC scenario was somewhat surprising, but can be explained by the modeling assumptions of FOHOW2. Given the initial age-class distribution and the modeling assumptions specified in the simulation protocol, the results of the BAU scenario were to be expected. However, experiments that use different models for long-term simulations always raise the question of uncertainties and the validity of the prognoses. Critical points in our analysis are the long simulation period and the assumptions of the models. In this context, we want to point out that the objective of this paper was not a prognosis of future forest conditions; rather, we wanted to understand the interactions and mutual dependencies between forest development and silvicultural treatment. We are completely aware that it is unrealistic to believe that our assumptions would hold over a time period of 140 years. However, to extract the pure effect of a treatment in an experiment, it is important to control for all other factors. From this point of view, it was necessary to maintain our assumptions over the full simulation period. For example, if we had used a simulation period shorter than 100 years, we would not have detected the sharp drop-off in harvesting rates in the CSC scenario. Uncertainties in the differences between the results of the scenarios were substantially reduced by modifying only those parameters for which the scenarios were defined in a different way (silvicultural measures), and by keeping the other framework conditions/behavior unchanged across the scenarios. Consequently, it can be expected that conclusions based on the different results of the scenarios due to the changed parameters are more robust than the general trend of the scenarios (e.g., time period when the forests turn from a carbon sink to a carbon source).

In Austria, changes in temperature and/or precipitation can have both a positive and a negative impact on forest growth. This is mainly caused by the mountainous terrain. Under the current climate, most of the high-elevation sites in the Alps are characterized by sufficient precipitation. On these sites, forest growth is mainly limited by low temperatures, and an increase in temperature would therefore increase forest growth. In the lowlands, forest growth is limited by low precipitation. Therefore, the overall effect in Austria depends on the balance between sites with positive effects and sites with negative effects [48]. To obtain better insights in these interactions, a more detailed analysis based on different climate scenarios would be required. However, such an analysis was not the scope of this paper. Here, we wanted to analyze the pure effects of silvicultural adaptation measures without confounding climate effects. For this purpose, we compared the scenarios within a world of unabated climate change. We emphasize that climate change mitigation policies did not have the intended effect, and current emission pathways are closer to RCP 8.5 than to more optimistic scenarios.

Our analyses demonstrated the effects of adaptive silviculture on various ecosystem services. Compared to the business-as-usual scenario, both climate change adaptation scenarios reduce salvage logging. However, the SRC scenario also reduces the carbon stock, but increases the harvesting rate. For the CSC scenario, the results are the opposite. Here, the carbon stock is increased, but the harvesting rate is reduced. Thus, there are clear tradeoffs between the different ecosystem services depending on the implemented climate change adaptation scenario. These findings are corroborated by the results of Seidl et al. [19] and Duncker et al. [51], who reported similar results on the complex interactions and tradeoffs between the various ecosystem services.

Our simulation experiment also reveals that a fundamental change in forest management, such as the CSC scenario, must be accompanied by a transformation in wood processing technology and innovation in wood utilization. The latter is particularly important for the production of long-lived wood products, which can provide a substantial contribution to avoid CO_2 emissions from fossil fuels and represent an important pool for carbon storage outside the forest [18,29,52]. Hence, for the production of long-lived wood products, it is important that the focus of future research is placed on the different options to substitute coniferous wood by the wood of broadleaved trees. If we are not able to manage these challenges, we will lose a substantial climate mitigation contribution from harvested wood products.

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