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Strategies for Climate-Smart Forest Management in Austria

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Abstract: We simulated Austrian forests under different sustainable management scenarios. A reference scenario was compared to scenarios focusing on the provision of bioenergy, enhancing the delivery of wood products, and reduced harvesting rates. The standing stock of the stem biomass, carbon in stems, and the soil carbon pool were calculated for the period 2010–2100. We used the forest growth model Câldis and the soil carbon model Yasso07. The wood demand of all scenarios could be satisfied within the simulation period. The reference scenario led to a small decrease of the stem biomass. Scenarios aiming at a supply of more timber decreased the standing stock to a greater extent. Emphasizing the production of bioenergy was successful for several decades but ultimately exhausted the available resources for fuel wood. Lower harvesting rates reduced the standing stock of coniferous and increased the standing stock of deciduous forests. The soil carbon pool was marginally changed by different management strategies. We conclude that the production of long-living wood products is the preferred implementation of climate-smart forestry. The accumulation of carbon in the standing biomass is risky in the case of disturbances. The production of bioenergy is suitable as a byproduct of high value forest products.

Keywords: carbon sequestration; forest management; simulation of aboveground stem biomass and soil; soil carbon; climate smart forestry

1. Introduction

Central European forests are currently a sink of greenhouse gases. The growth rate of forests has been increasing for decades because of nitrogen deposition, elevated concentrations of carbon dioxide (CO_2) and higher temperatures [1,2]. In addition, due to abandonment of marginally productive agricultural land in low elevation areas and the expansion of mountain forests beyond the previous upper timberline, the forest area has increased [3,4]. New young forests have a high growth rate and comprise an effective sink for carbon. Forestry is the only sector of the economy that acts as a net sink for CO_2. Terrestrial ecosystems in Europe already sequester 7% to 12% of the anthropogenic CO_2 emissions, even though the potential of forests is not fully utilized [5–8].

Historically, Austrian forests have emerged from a low level of forest area in the 19th century. A growing population had required the expansion of agricultural land. High elevation forests were cleared and converted to pastures. This land-use change soon triggered soil erosion and increased the risk of damages from flooding and avalanches [9]. As an immediate mitigation measure a policy of sustainable forest management was implemented, that was gradually modified and improved. For many decades it was deemed desirable to protect and possibly expand the forest area. Partially as a legacy of this policy, a high forest cover was reached and the standing stock of the tree biomass is still increasing [10]. Regional forest management plans call for an alleviation of this strategy and rather aim at increased harvesting rates in order to close the gap between harvest and growth and to efficiently use the wood resources in the bioeconomy [11].

The need to effectively and immediately mitigate climate change has been expressed and calls for action in all sectors of the economy [12]. Measures taken in the land-use sector are popular because the technology is already available and immediately implementable [13]. Forest management provides three mitigation effects. Forests are (i) a resource for wood products that can substitute materials with a larger ecological footprint, by (ii) providing renewable energy from fuel wood and byproducts of wood processing, and (iii) sequestering CO_2 from the atmosphere upon growth. Several national studies were seeking an optimal tradeoff between avoided emissions by the provision of wood products and the reduction of the carbon sink by increased harvesting rates. The short- and long-term effects of the compared strategies differed widely. The best climate change mitigation effect is achieved when wood is converted into long-lived products that are suitable for wood cascading, where the same wood unit is used in several, successive product cycles. Forest conservation concepts with the aim of maximizing the carbon storage in the tree biomass are less effective when accounting for the risk of damages by natural disturbances [14–19].

Climate-smart forestry is a comprehensive concept where, within the margins of sustainable forest management, measures are sought that contribute to the mitigation of climate change. It includes reducing emissions of greenhouse gases, building resilience in existing forests, and increases in forest productivity. Climate-smart forestry seeks synergies with other policies such as enhancement of biodiversity, provision of ecosystem services from forests, and the establishment of a strong bioeconomy. There are regional differences in the most effective measures, depending on the traditional use of forests and its legacies on present forests, and on the disturbance regime. A common denominator of case studies conducted in Spain, the Czech Republic, Ireland are medium- and long-term climate benefits of material substitution that are possible when forests are actively managed and when harvesting levels are increased within the margins of sustainable forestry [8,20].

Here we focus on climate-smart management strategies for Austrian forests. We confine our view to concepts that are under the direct control of the forestry sector and are supported by stakeholder groups. The strategies are not necessarily compatible or even mutually exclusive. The starting point of our simulations is given by the latest assessment of the forest resources, i.e., the data of the National Forest Inventory 2007 and 2009. The continuation of business-as-usual forestry as reference was compared with a bioenergy scenario, two scenarios with increased harvesting rates, and a scenario with reduced harvesting. Within the concept of sustainability the chosen management options for Austrian forests are possible. All of them accommodate expectations of forest owners, forest policy, and society. As response variables we chose the standing stock and carbon pool of the stem biomass and the soil carbon pool in order to indicate the long-term effect towards climate-smart forestry. A detailed life-cycle analysis considering the effect of forest management, material substitution, and energy provision already been presented in a companion paper [14]. Here we examine and evaluate the forestry part with respect to carbon dynamics in the stem biomass and soils.

2. Materials and Methods

2.1. Characteristics of Austrian Forests

Austrian forests comprise 4×10^6 ha land, translating in a forest coverage of 47.6%. 1.2×10^6 ha are managed by private forest enterprises, 0.6×10^6 ha by the Austrian State Forests, and 2.1×10^6 ha belong to the category "small forests", where a large number of forest owners manage 200 ha or less, each. The forest area increases as consequence of abandonment of agricultural land. The standing stock of stem wood is 1135 × 10^6 m^3, or 337 m^3 ha^{-1}. The annual increment is 30.4 × 10^6 m^3, or 9 m^3 ha^{-1}. The harvest rate is 25.9 × 10^6 m^3, or 7.7 m^3 ha^{-1} (http://waldinventur.at). In addition to the domestic timber production 9.9 × 10^6 m^3 are annually imported. Forest enterprises and Austrian State Forests harvest at a rate close to the annual increment. The surplus of increment over harvesting in the national statistics is a consequence of the low management intensity on forest land that is managed by smallholders.

Approximately 6.6 × 10^6 m^3 fuel wood are produced per year, equally supplied by traditional smallholder forestry in rural areas and from forestry operations of large enterprises. Along the entire value chain of timber processing about 50% of the wood is used as energy [21,22].

The plots of the Austrian National Forest Inventory are arranged in clusters on a grid with a mesh width of 3.89 km. In total, there are 11,000 forest plots. The monitoring of forest resources is done at intervals of about 7 years. At each plot a large number of parameters is assessed in order to meet the information needs of forest policy and international reporting obligations [23,24].

2.2. Forest Management Scenarios

A stakeholder dialogue was established in order to define clear and transparent narratives for five forest management scenarios. The stakeholder group represented forest policy, forestry enterprises, the pulp & paper industry, saw mills, nature conservationists, and forest scientists with expertise in national market dynamics, forest ecology, silviculture, and national greenhouse gas emission reporting. In a discussion process the parameters and variables of the scenarios were defined.

The "Business-as-usual" or "Reference" scenario is characterized by

- The demand for timber quantity and quality is equal to the observed situation of the years 2007 and 2009, according to data of the Austrian National Forest Inventory.
- The National Renewable Action Plan 2010 is implemented in the future and the supply increases due to higher market prices for fuel wood [25].
- The annual cuttings increase from 2010 to 2020 in accordance with the observation that the forests had been under-utilized in the past.
- The forest area remains constant.

The "Bioenergy" scenario (Scenario 1a) is characterized by

- The Renewable Action Plan 2010 [25] is further developed and the demand for fuel wood increases due to higher market prices for fuel wood.
- The demand for timber increases, in particular for hardwoods with a high caloric value.
- Increased forest management intensity is implemented in the form of more thinnings and shorter rotation periods.
- A decline in standing stock of biomass is expected and accepted.

The "domestic wood products" scenario (Scenario 1b) is characterized by

- An increased demand for wood and wood products, partially triggered by government subsidies, modified regulations for buildings, and new technologies.
- Attractive market situations for timber, and low prices for fuel wood stimulate the demand.
- Moderate imports of timber are still possible. However, a larger quantity of timber derives from national forest resources because growing wood processing capacities in neighboring countries constrain timber imports.

The "import-assisted wood products" scenario (Scenario 1c) is characterized by

- The characteristics of Scenario 1b.
- An increasing rate of timber imports that alleviate the pressure on national natural resources.

The "reduced-harvest" scenario (Scenario 2) is characterized by

- Stepwise reduction of the harvesting rate by 5% until 2020 to 15% after 2050.
- Enlargement of nature conservation areas in the wake of Natura 2000 and the European Biodiversity Strategy [26].
- The protected area goes from currently 1.2% of the production forest area to 5% in the year 2100, in accordance with the expected unfolding political agenda on nature conservation.

2.3. Climate

For the purpose of our project we sought climate scenarios reflecting the required spatial resolution of our forest inventory data. The required climate parameters for the forest growth model and the soil carbon model are derived from monthly data of precipitation and air temperature. The small-scale variability of geographic conditions, defined by the strong relief of mountain regions in Austria, make interpolations between locations of weather stations rather unsatisfying. At the time of project preparation the available regional climate scenarios were unsuitable. Only now, based on EuroCordex and OEKS 15, more reliable regional scenarios are available [27,28]. Therefore we created our own climate scenarios based on daily measurements of temperature and precipitation taken by the Austrian Hydrological Survey during the years 1980 to 2010 (https://ehyd.gv.at/). First, the climate parameters for the 11,000 points of the National Forest Inventory were linearly interpolated and corrected for effects of elevation. A time trend of temperatures was created by tilting the average temperature of the years 1980 to 2010 in order to obtain a warming trend of 3.5 °C in 90 years, corresponding to the RCP scenario 8.5 and the SRES scenario A1b [29,30]. In order to create noise to the temperature data we randomly drew monthly values from the measurements of the years 1980 and 2010 and adjusted the temperatures accordingly. For the precipitation no clear annual trend is expected during the 21st century [30]. Therefore the mean precipitation of the years 1980 to 2010 was used and noise was superimposed as described for the temperature data.

2.4. Simulation of the Aboveground Biomass

The growth simulator Câldis was used [31,32]. The model requires climate, single stem parameters, and site conditions as input parameters. For the initial forest characteristics of the simulation period the data of the plots of the Austrian Forest Inventory 2007–2009 were used. The growth model was run in yearly timesteps. A stem could either remain in the category "standing stock" or be assigned to the categories "thinning operation", "final harvest", or "tree mortality".

The harvesting module was run in 1-year time segments. The modelled timber extractions were adjusted to the externally defined demand of the timber market (Figure 1). The choice of harvested sites followed a strict protocol: Based on the market request, the standing stock of all inventory plots was ranked. For each plot a contribution margin was calculated in order to quantify the expected revenue from harvesting. Protection forests and forests in nature conservation areas were flagged because their utilization follows a different strategy. The diameter distribution within each plot was used in order to distinguish whether the possible intervention would qualify as a thinning operation or a final harvest. Thereafter, the plots with the highest contribution margins were selected for harvests until the externally defined timber demand was satisfied. Our protocol intends to reflect the decision process that would be followed in a forest enterprise where forests with a high contribution margin are harvested preferably and more expensive interventions are avoided when possible.

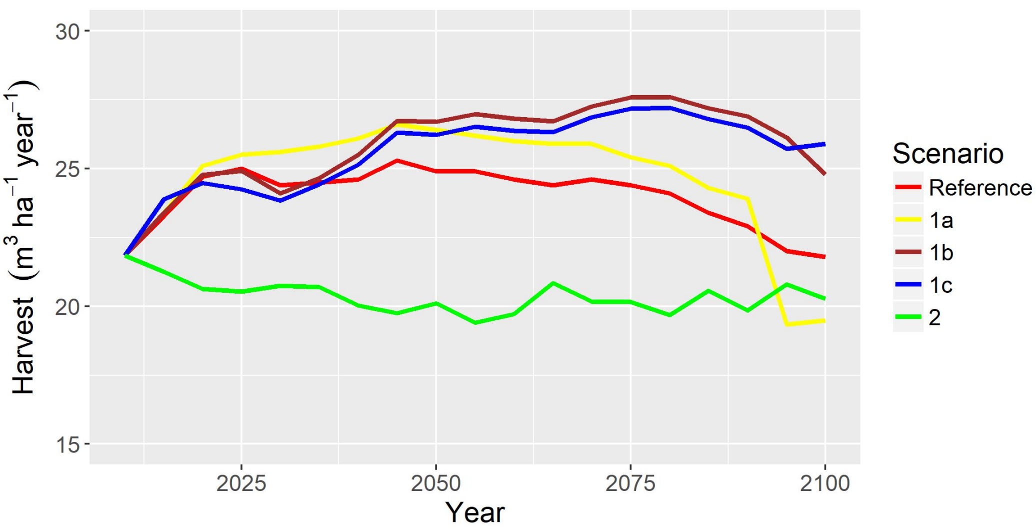

Figure 1. Harvested stem volume including bark in different forest management scenarios.

The stem volume was converted to carbon mass. For coniferous trees a conversion factor of 410 kg m^{-3} was used. For deciduous trees the factor is 680 kg m^{-3}. In order to convert biomass in carbon mass we assumed a carbon content of stemwood of 50%. The factors for tree density were chosen according to the methods used for the National Inventory Report under the United Nations Framework Convention on Climate Change and the Austrian timber trade rules [7,33].

2.5. Simulation of the Soil Carbon Pool

The soil carbon model Yasso07 was used to simulate the temporal trend of soil carbon. The core of Yasso07 is a module describing the decomposition of soil organic matter [34–36]. Yasso07 requires the quantity of the above- and belowground flux of organic matter to the soil, the climatic conditions, and the chemical quality of the incoming organic matter as input variables.

The climate parameters annual precipitation, annual mean air temperature, and temperature difference between the coldest and warmest month were taken from the same dataset as the climate data for tree growth. For each tree the total biomass was calculated from stem diameter and height by regionally valid biomass functions and divided into the aboveground compartments stem, branches, needles and leaves, and the belowground parts, i.e., coarse roots and fine roots [37]. The biomass of each compartment was converted into carbon mass. For each compartment an annual flux of carbon to the soil was calculated. The chemical quality of the aboveground and belowground litterfall was taken from the manual of Yasso07 and nationally available data compilations. The flux of organic matter was calculated from the output of Câldis. The growth simulator yielded for each tree the characteristics "tree species", "stem height", "stem diameter", "stem volume" and the annotation whether the tree remained in the stand, was extracted, or had died off. The procedure of creating the input file for Yasso07 is described in detail [38,39].

The simulation was repeated 10 times for each plot in order to reflect the uncertainty of model parameters. The output of Yasso07 were averaged for each plot. The validity of Yasso07 for Austrian conditions had been tested previously and was judged satisfactory [39,40].

3. Results

3.1. Aboveground Stem Biomass

Figure 2 shows as starting point 320 m^3 stem wood per hectare, when combining the standing stock of stemwood in coniferous and deciduous forests. Roughly, 80% of the standing stock comprises coniferous trees (spruce, fir, pine), and 20% are deciduous trees (beech, oak, ash). In the Reference scenario the standing stock declined by 9% between 2010 and 2100, consistent with the results of the National Forest Inventory 2007 and 2009. The bioenergy scenario (1a) maintained a similar standing stock of coniferous trees as the reference scenario, but showed a strong decrease of the standing stock of hardwood trees, because deciduous trees are preferentially cut when energy from woody biomass is demanded. At the end of the simulation period the standing stock of stem biomass was lowered by 17%. Scenario 1b, that reflects a high demand for timber from domestic production, led to a decrease of 29% of the standing stock of stem biomass until the end of the simulation period. The simulated demand for timber was primarily met by coniferous wood, and to a smaller extent by wood from deciduous trees. Even with higher timber imports and a lighter pressure on domestic forests the standing stock of stem wood declined by 25% (Scenario 1c) during the simulation period. The reduced-harvest scenario (Scenario 2) showed a different pattern. Overall, the standing stock of stem biomass increased by more than 34%. Whereas the average stock of coniferous trees at the end of the simulation period was similar to the reference scenario, the standing stock of stems from deciduous trees was increasing markedly. By the year 2100 the coniferous and deciduous forests had almost reached parity.

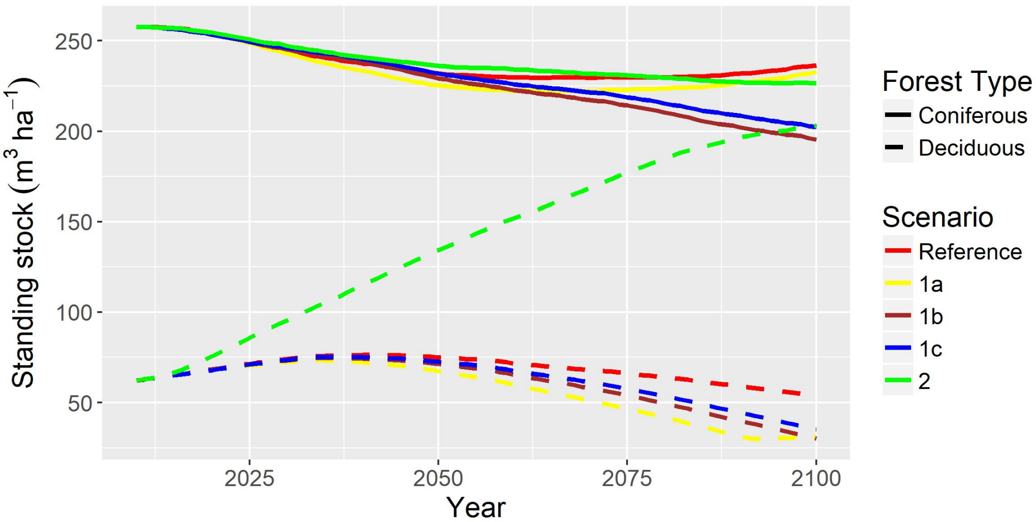

Figure 2. Development of the stem wood volume in different forest management scenarios separated by coniferous and deciduous forests.

Accounting for the differences in wood density, the difference between management scenarios was even larger (Figure 3). Dense timber from deciduous forests, that initially held about 20% of the stem volume, contributed almost 50% of the carbon mass in stems. The Reference scenario and scenarios 1a, 1b and 1c showed declining carbon masses in stems according to the intended increase in harvesting rates. In the reduced-harvest scenario (scenario 2) already by the mid of the century deciduous trees were storing a higher carbon mass than coniferous forests. By the end of the simulation period two thirds of the stemwood carbon was in deciduous forests.

The harvesting rate started at the level of 21.8×10^6 m^3, as reported in the National Forest Inventory of 2007 and 2009. During the simulation period the harvest rate of the reference scenario increased and returned to the initial level at the end of the simulation. In scenario 1a the harvesting rate increased strongly at first, but dropped below scenarios (1b, 1c) by the mid of the century, and eventually even below the reduced-harvest scenario (2). The reason was that the requested timber from deciduous trees, suitable for bioenergy, could not be delivered any longer (Figure 1). In scenarios 1b and 1c the harvesting rate was raised by 13% and 18%, respectively, and remained high until the end of the simulation period. The reduced-harvest scenario (2) showed a slight decrease in the harvesting rate, as compared to the beginning of the simulation, reflecting that the area of unmanaged forest was gradually increased.

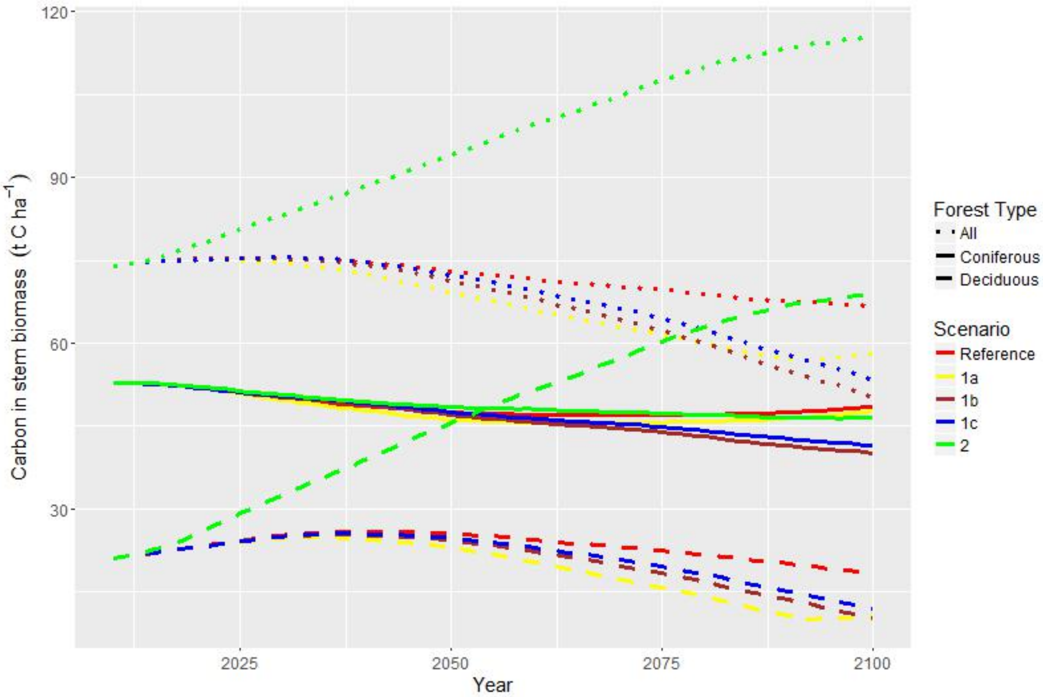

Figure 3. Development of the carbon mass in stem wood in different forest management scenarios separated by coniferous and deciduous forests and as total carbon stock.

Figure 4 set off at the currently observed annual increment of 9.5 $m^3 ha^{-1}$. In the reference scenario and in the timber mobilization scenarios (1a, 1b, 1c) the annual increment was decreasing because the standing stock of tree biomass was reduced. The temporal pattern was irregular and was reflecting both the harvesting operations and exceptional climate conditions that led to short periods of growth declines in all scenarios, e.g., in the year 2059. In the reduced-harvest scenario (2) the annual increment increased in the first decades. Later, the increment declined, presumably as a consequence of a higher share of overmature and slower growing deciduous forests.

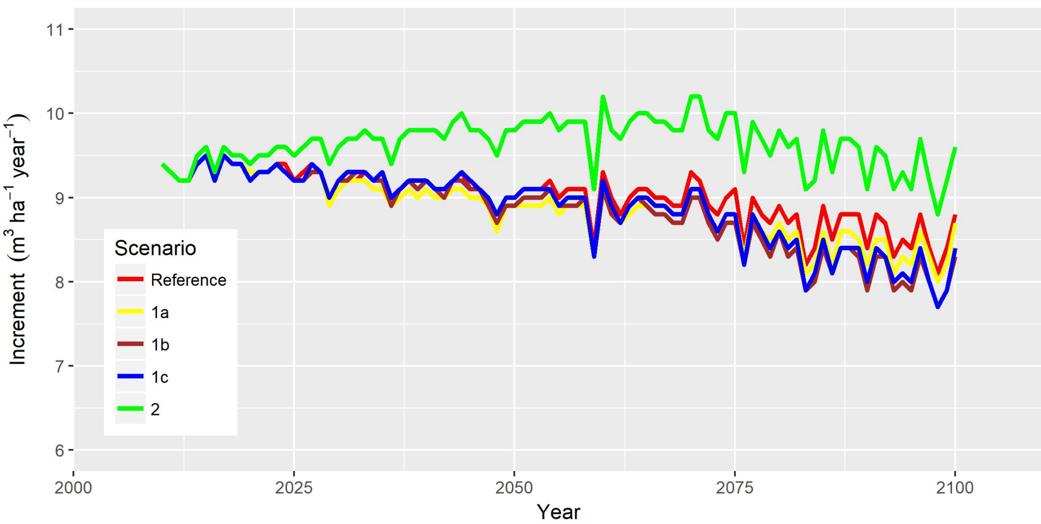

Figure 4. Development of the current increment in different forest management scenarios.

3.2. Soil Carbon Pool

The soil carbon pool was hardly affected by different forms of forest management according to the reference scenario and scenarios 1a, 1b, 1c. Obviously, soils are responding much slower to external drivers such as climate effects and forest management. The soil carbon pool increased somewhat and returned to the initial level by the end of the simulation period. Only in the reduced-harvest scenario, where the standing stock of the tree biomass was highest, the soil carbon pool was increased substantially (Figure 5).

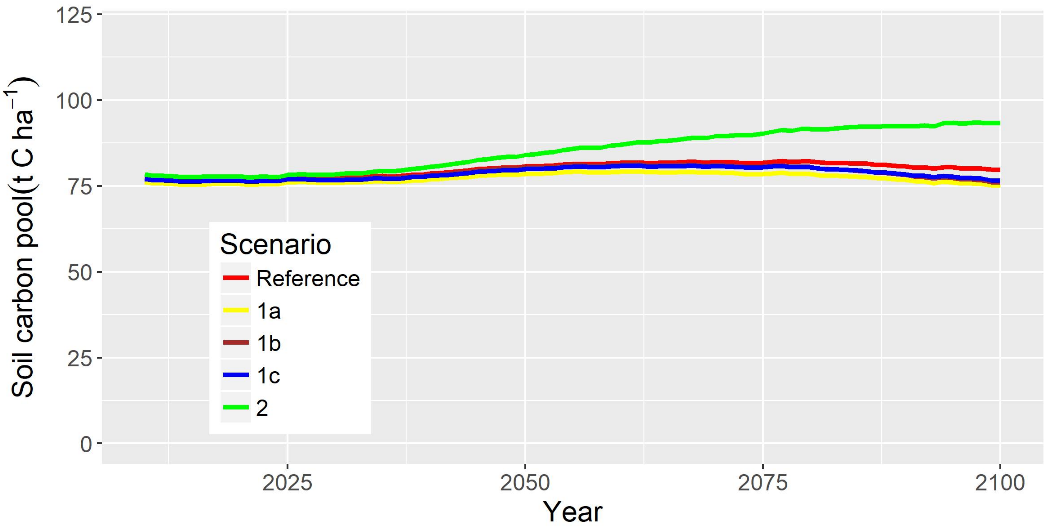

Figure 5. Development of the soil carbon pool in Austrian forests in different forest management scenarios.

4. Discussion

We compared several scenarios of forest management that emphasized different policy goals within sustainable forest management. The overall goal was the provision of science-based advice to policy makers. Increasing stocks of the tree biomass are a consequence of an increase in the forest area, backlogs in silvicultural measures such as thinning, and a consistent surplus of increment over harvest rates [10]. Taken together, plentiful resources for a viable bioeconomy are available. In addition, forests harbor a rich biodiversity and are attractive for nature conservation programs. Due to the CO_2 adsorption in the tree biomass via photosynthesis the Austrian forests are currently a strong carbon sink and Austria is both committed and obliged to maintain this sink [7]. However, the sink strength of forests is limited by the frequency and severity of disturbances. Besides climatic drivers a change of the forest structure towards overmature and dense stands has contributed to an increased disposition for disturbances in Central Europe [41–43]. In view of these findings it is necessary to take measures to increase the stability of forests.

Our simulation experiment focussed mostly on activities that are controlled by the forestry sector. A range of options of “climate-smart forestry” is available. We did not account for an expansion of forests because the process is mostly driven by land management decisions taken in agriculture and the future trend is unknown. A change in the tree species composition was not built into the scenarios because no converging views were identified in the stakeholder process during scenario definitions. Instead, the tree species composition was controlled primarily by management decisions, and also by the climate-dependent tree regeneration module of Câldis. In addition, productivity enhancing measures such as future nitrogen fertilization effects were ignored. We acknowledge that nitrogen deposition will have a significant role for forest productivity in the next decades [2]. However, we could not sufficiently constrain such effects and did not accommodate them in our scenarios. As external factor for forest management we assumed a growing demand for wood products as consequence of successful information campaigns by stakeholders and an increasing awareness of the population of sustainability issues. Moreover, we conceded that the public calls for an increase in nature conservation areas where forest management is limited or even banned.

The bioenergy scenario (1a) tested whether an increased demand for renewable energy from tree biomass can sustainably be delivered. The pursued aspects of "climate-smart forestry" are the substitution of fossil energy. In addition, we assumed that a part of the woody biomass for bioenergy is collected from thinning operations. Presently, there are many forests where thinnings are overdue, but not implemented due to high costs. Thinnings would qualify as 'improved forest management' in the context of "climate-smart forestry". A rising demand for fuelwood would increase the market prices for thinning residues. Presently, already 50% of the wood is used as bioenergy [21,22]. A major contribution to the fuel wood comes from areas where natural disturbances have damaged the forests, and from byproducts of timber processing. Concerns that incentives for bioenergy lead to an increasing production rate of fuel wood at the expense of sustainability have been expressed [44,45]. Under the market conditions in Austria this risk is negligible. Less than 30% of timber is primarily cut as fuel wood, primarily in rural areas and in forests managed by smallholders [46]. In our simulations the bioenergy scenario led to a strong decrease of the standing stock of deciduous trees (Figure 2). Towards the end of the simulation period the required amount of hardwood could no longer be delivered and the harvesting rate dropped (Figure 1). We conclude that a 20%-increase of energy production from woody biomass is not easily reconcilable with conditions in Austrian forests. For a successful implementation of the strategy it is necessary to take additional silvicultural measures in order to increase the growth rate of the forests, or modified harvesting processes that extract more biomass. Such strategies generally imply an increased demand for nutrients and are restricted to fertile sites [47].

Our wood product scenarios (1b, 1c) did not accommodate foreseeable trends in wood technology and timber markets, but maintained the market situation of harvested wood products of the years 2000 to 2010 until the end of the simulation period. Scenarios 1b and 1c allowed the reduction of the standing biomass stock in order to proactively position wood products in competition with other materials (concrete, steel, glass) on the market, thereby fitting into the concept of "climate-smart forestry". The two scenarios differed with respect to the availability of timber on the international market. The standing stock in the mobilization scenarios (1b, 1c) declined by the end of the century by approximately 15% as compared to the reference scenario. The decline of the standing stock of coniferous trees was stronger than that of deciduous trees because construction wood was the main commodity. The difference between the two scenarios with respect to the standing stock of tree biomass, soil carbon and the harvesting rate were small (Figures 1, 2 and 5). However, Figure 3 showed that the carbon mass in the stem biomass consistently declined. In order to control this trend, the management pattern of the two scenarios can only be upheld for several decades. Later the harvesting pattern needs to be adjusted to a lower level.

The reduced-harvest scenario (Scenario 2) reflected the growing desire for unmanaged forests in order to expand National Parks and nature conservation areas. From the perspective of the availability of resources the scenario is justified. We have no evidence that we are running out of timber and setting aside forest land for the purposes of nature conservation is already a reality [48]. A peculiarity of the reduced-harvest scenario (Scenario 2) was the continuous increase of the standing stock of deciduous forests, but low effect on coniferous forests (Figure 2). This reflected that the timber market prevailed at the previous level, but the demand for timber in the still-managed forests was mostly met from coniferous trees. In our dataset, the dedication of forests to a special conservation status applied dominantly for deciduous forests. We conclude that highly productive coniferous forests are of lesser relevance for biodiversity programmes and/or forest owners may be less willing to set aside highly productive sites for nature conservation programmes. Within only one tree generation the ratio of coniferous to deciduous trees went from 5:1 to almost parity and the majority of stemwood carbon was stored in deciduous trees (Figure 3). With respect to carbon sequestration the scenario was highly effective. Impressive carbon stocks in old-growth forests have been used as indicator that low-intensity forest management is a viable option for enhancing the relevance of European forests for climate change mitigation [49,50]. However, the strategy is not necessarily climate smart. Positive effects are lost when a reduction in the domestic timber production and an increase in nature conservation areas is compensated by the import of timber and wood products from other regions [51]. Such an effect would be a classical "leakage" [52]. In addition, the sequestration of CO_2 in living trees is transient. It is most successful until the forests reach dimensions that are more vulnerable to disturbances. Tall and dense forests are susceptible to storm damages, often followed by insect infestations. The slowly accumulated carbon in the tree biomass can be released quickly to the atmosphere after stand-destructing disturbances [41,42,53,54].

Secondly, job opportunities in timber processing are reduced when less timber enters the market [55]. From the viewpoint of a balance between ecological needs and human well-being it seems justified to thoroughly define a regionally valid reference level for the sustainable standing stock of tree biomass and to manage forests within a reasonably narrow margin around that reference level.

The reference scenario was performing very well in comparison with the other scenarios. The results confirmed that the management of Austrian forests has, over centuries, developed into a truly multifunctional concept that can accommodate a wide range of stakeholder expectations. Forestry is an important pillar of the rural economy. The reference scenario achieves many goals of "climate-smart forestry". Improvements are sought in the interaction of forest policy with smallholder forest owners where the harvest rate is currently over 20% below the increment. A promising trend of an increasing demand for timber and wood products was evident from forest inventory data collected in 2007 and 2009. The trend was disrupted during the economic crisis of the year 2008 and has not fully recovered since then [56]. Campaigns to increase the awareness of consumers towards the advantages of wood products with respect to environmental benefits have not yet fully stimulated the demand for timber. In the wake of natural disturbance events a large timber quantity was released to the market and currently forest managers are reticent in their harvesting operations until timber prices go up [46].

The decreasing increment rate of the forest in the reference scenario and all timber mobilization scenarios (1a, 1b, 1c) was mostly a consequence of the reduction of the standing stock of biomass (Figure 4). After many years of increasing growth rates due to harvesting rates below the increment, the elongation of the growing seasons, fertilization effects from nitrogen deposition, and elevated concentrations of CO_2 in the atmosphere the growth rates apparently stabilize or even decline. Despite many efforts it is still difficult to clearly separate the effects of different growth-accelerating processes [2,3,57,58]. The amount of timber delivered to the market can be maintained when forest management strategies are modified and shorter rotation periods are chosen [59]. However, climate change may also reduce the growth rate of forests. Evidence is given by the increment rate of the reduced-harvest scenario (Scenario 2). It increased until the mid of the century, partially due to increasing biomass stocks and partly as a response to climate parameters. However, in the second half of the century the increment rate slightly declined despite rising biomass stocks. A factor besides climate change is the age distribution of forests. In order to satisfy the timber demand of the market the rotation period in the still-managed forests needs to be lowered. The unmanaged forests are slowly developing into a state of over-maturity with lower growth rates. This effect is becoming apparent after several decades. In all scenarios the noise of the increment data was similar, indicating that climate variables such as exceptionally dry summers in the years 2059, 2076, and 2083, according to the chosen climate scenario, altered increment rates in conformity (Figure 4).

Soil carbon pools responded to different timber mobilization scenarios (Scenarios Reference, 1a, 1b, 1c) and altering climatic conditions only to a small extent (Figure 5). The total soil carbon pool of Austrian forests slowly responded, intermittently rose and returned to the initial level by the end of the century. The exception was the reduced-harvest scenario (Scenario 2). The shown trend is a consequence of the model logic of Yasso07 where the flux of organic matter to the soil is driven by the standing stock and the amount of harvesting residues that remain on-site. The increasing standing stock of the biomass leads to the accumulation of soil carbon. The effect is leveling off and the trajectory of the soil carbon pool is almost flat at the end of the simulation period. For the slow response of the soil carbon pool the term "iron law of site properties" has been coined [60].

Our simulations have shown that the chosen forest management scenarios can be satisfied for several decades. In order to make a judgement on the most appropriate concept for climate change mitigation we have performed a life-cycle analysis, that was presented in a companion paper [14]. The material use of products from domestic timber sources gave the highest climate benefit. Within the 90 years of our scenarios the avoided emissions equalled approximately 20 years of total annual Austrian emissions. The largest effect of different forest management strategies was attributable to avoided emissions that follow from substitution of non-wood materials with wood products, and the substitution of fossil energy with energy from wood products. The substitution of fossil energy in the bioenergy scenario (1a) is obvious. But also in scenarios aiming at the increased provision of wood products, a considerable energy substitution effect takes place, owed to the high percentage of combustible residues of timber processing. The climate change mitigation potential of long-lasting wood products is high. The climate change mitigation sets in with a lag time of decades when the forests that are subject to specific management strategies are harvested and the timber is turned into wood products that substitutes for other materials. The mitigation effect ends when the material substitution is finished. The effects of forest management on carbon sequestration are happening quicker and are wearing off after several decades. After the saturation of the carbon sink that reflects the respective forest management strategy, the carbon sequestration effect declines. This analysis emphasizes the understanding that forest management can buy time, but cannot offer the ultimate solution for climate change mitigation.

When comparing the results of different forest management options in order to mitigate climate change it is advised to look beyond the borders of forestry. Using wood biomass primarily for the production of bioenergy is not an optimal solution. It is questionable whether timber as a renewable resource should be converted quickly into heat after a growth process of several decades. Byproducts of timber processing are plentiful and are the main pillar for the production of energy from woody biomass. It is certainly preferable to take advantage of the remarkable technological properties of wood, to produce long-living wood products and burn them at the end of their life cycle. An additional reasoning is the strengthening of the economy in rural areas where processing of timber creates job opportunities and diversifies the market [61].

Currently, strategies for substantial reductions in emissions of greenhouse gases are sought and it is recognized that zero emissions and even negative emissions are required to reach the goals of climate change mitigation as agreed in Paris 2015 [12]. In these scenarios sequestering CO_2 from the atmosphere via forest management plays a vital role. Despite doubts in the effectiveness of Bioenergy, Carbon Capture and Storage (BECCS) the appropriate management of forests will have to be used as mitigation strategy against climate change [13,62,63].

5. Conclusions

The presently available Austrian timber resources allow the implementation of widely differing forest management scenarios. The currently used management practice, which is reflected in the Reference scenario, ensures sustainable forestry and supports the economy in rural areas strongly. Episodes of harvesting rates beyond the actual growth rate are possible.

Shifting from the reference scenario to a bioenergy scenario (Scenario 1a) is a politically desirable option for the implementation of the Renewable Action Plan [25]. It implies an increased demand for hardwoods as fuelwood and could lead to the implementation of overdue thinning operations in order to deliver the requested wood quantity. The bioenergy is mostly a temporally viable option. The resources of hardwoods are predicted to run out after several decades. Additional measures such as silvicultural interventions and modified harvesting operations are required.

Scenarios 1b and 1c are aiming at an increased supply of wood products to the market. They differ with respect to the origin of the resources. Scenario 1b utilizes mostly timber from domestic production whereas scenario 1c reflects a higher percentage of timber imports. Scenarios 1b and 1c are giving similar results with respect to increment, standing stock of stems, and soil carbon pools. However, they are reducing the standing stock of tree biomass by 25% within the simulation period. This reduction is intended because under-utilized timber has been accumulating for several decades. Accordingly, the scenarios are called "mobilization scenarios". Within approximately 90 years, the standing stock of Austrian forests would return to the conditions of the inventory period 1971 and 1980 [10].

The reduced-harvest scenario (Scenario 2) ultimately leads to a slight decrease in the standing stock of coniferous forests because the demand of the timber industry needs to be satisfied. A strong and consistent increase in the standing stock of deciduous forest reflects a tendency that they are preferentially included in nature conservation programs. This may be both driven by the ecological value of these forests, and the lower relevance or availability of highly productive forests for nature conservation programmes. The reduced-harvest scenario is superior to the other scenarios with respect to the sequestration of carbon in the stem biomass and the soil. It is highly effective when the objective is the accumulation of carbon in forest ecosystems. However, the scenario compromises efforts of increasing the supply of long-living wood products.

The Austrian forests can sustainably deliver the timber resource for different management strategies. The presently implemented reference scenario is already multifunctional and climate-smart. Considering the risks involved in building up large carbon stores in ecosystems it seems preferable to pursue a strategy of active forest management. Thereby, large carbon pools can be maintained in the standing stock of the tree biomass and the soils, and also long-living wood products can be brought to the market.

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