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OPINION

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# The climate change mitigation effect of bioenergy from sustainably managed forests in Central Europe

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## Abstract

We compare sustainably managed with unmanaged forests in terms of their contribution to climate change mitigation based on published data. For sustainably managed forests, accounting of carbon (C) storage based on ecosystem biomass and products as required by the United Nations Framework Convention on Climate Change is not sufficient to quantify their contribution to climate change mitigation. The ultimate value of biomass is its use for biomaterials and bioenergy. Taking Germany as an example, we show that the average removals of wood from managed forests are higher than stated by official reports, ranging between 56 and 86 mill. $m^3$ $year^{-1}$ due to the unrecorded harvest of firewood. We find that removals from one hectare can substitute 0.87 $m^3$ $ha^{-1}$ $year^{-1}$ of diesel, or 7.4 MWh $ha^{-1}$ $year^{-1}$, taking into account the unrecorded firewood, the use of fuel for harvesting and processing, and the efficiency of energy conversion. Energy substitution ranges between 1.9 and 2.2 t $CO_{2\ \mathrm{equiv.}}$ $ha^{-1}$ $year^{-1}$ depending on the type of fossil fuel production. Including bioenergy and carbon storage, the total mitigation effect of managed forest ranges between 3.2 and 3.5 t $CO_{2\ \mathrm{equiv.}}$ $ha^{-1}$ $year^{-1}$. This is more than previously reported because of the full accounting of bioenergy. Unmanaged nature conservation forests contribute via C storage only about 0.37 t $CO_{2\ \mathrm{equiv.}}$ $ha^{-1}$ $year^{-1}$ to climate change mitigation. There is no fossil fuel substitution. Therefore, taking forests out of management reduces climate change mitigation benefits substantially. There should be a mitigation cost for taking forest out of management in Central Europe. Since the energy sector is rewarded for the climate benefits of bioenergy, and not the forest sector, we propose that a $CO_2$ tax is used to award the contribution of forest management to fossil fuel substitution and climate change mitigation. This would stimulate the production of wood for products and energy substitution.

KEYWORDS

climate change mitigation, $CO_2$ equivalentss, $CO_2$ tax, energy and product substitution of fossil fuel, nature conservation, sustainable forest management, unmanaged forest, wood energy

## 1 | INTRODUCTION

There is general agreement that forests have the potential to be a carbon sink large enough to compensate emissions from agricultural land in Europe (IPCC, 2013; Schulze et al., 2009). Despite this, it remains unclear how the forest sector could be credited for this contribution to climate change mitigation. The Kyoto Protocol allowed accounting for changes in forest carbon stocks as a sink (UNFCCC-COP3, 1997) and this was extended in the Durban conference of the parties (UNFCCC-COP17, 2011) as well as the Paris Agreement to an additional accounting for carbon in wood products of wood industries (Sato & Nojiri, 2019; UNFCCC-COP21, 2015). Following the definitions of the IPCC Guidelines for carbon sinks and products, the accounting of bioenergy remained a separate issue. The production of renewable energy should be accounted for in the energy sector (IPCC Guidelines, 2006; Schulze, Stupak, & Hessenmöller, 2019). Thus, the forestry sector remained at the level of the Kyoto Protocol after the Durban conference.

This accounting scheme has no consequences for computing national emissions as long as the forest biomass is combusted in the same country as it has been produced. However, since harvesting is accounted for as an emission (IPCC Guidelines, 2006), landowners are rather punished than getting credited for sustainably managing their forest, and they may have to pay a $CO_2$-emission tax in the future (e.g., https://sustainable-economy.org/forest-carbon-tax-reward-creating-jobs-carbon-woods/).

In this context, "sustainability" is defined by the long-term time trends in wood volume or basal area at landscape scale. In Germany, 10 year management plans of forest properties provision that wood volumes or basal areas remain constant at landscape scale. At this point, growth balances harvest, depending on site conditions. Sustainability does not define the level of wood stocks that should be maintained: forests can be sustainably managed at different levels of wood volume, dependent on the production objectives (Burschel & Huss, 2003; Kramer, 1988). In this study, sustainability is based on aboveground parameters, and it is viewed at timescales of a rotation period. Exploitation of forests where harvest exceeds growth is not permitted in sustainably managed forests. Also, land use change and associated destruction of forest are not part of a sustainability scheme.

According to the United Nations Framework Convention on Climate Change, the entity that reports commitments and reductions of greenhouse gas (GHG) emissions is the individual nation. Due to the accounting for changes in carbon stocks only, forestry got under increasing pressure by nature conservation groups who suggest that the mitigation effect of forests could be increased by taking forest land out of management (Greenpeace, 2018; WBW, 2018). The contribution of wood products to mitigation is much less understood, and therefore, the facts are ignored that (a) the objectives of the owner and not harvest determine forest carbon stocks as a baseline of sustainability; (b) forest growth is enhanced by proper management (Bouriaud, Don, Janssens, Marin, & Schulze, 2019; Bouriaud, Marin, Bouriaud, Hessenmöller, & Schulze, 2016; Ciais et al., 2008); (c) carbon storage in forest products may prolong the lifetime of sequestered carbon compared to onsite release of $CO_2$ by decomposition; and (d) products that are out of use can serve for energy production in addition to the primary and secondary wood, instead of being disposed of in other ways.

Arguments favoring forest conservation also ignores that thinning increases drought tolerance and reduces the risk of wind throw that increases with stocking and tree height, mainly in spruce, and that biodiversity requires an open canopy for light demanding species. They ignore the fact that wood is being harvested as raw material and in order to accomplish the needs of society. Residues and products at the end of their lifetime are eventually used for bioenergy replacing fossil fuel in Germany (energy substitution; EEG, 2003), even though the forest sector does not get credits for the use of wood for energy production. The anticipated "Forest-Climate-Foundation" (http://waldklimafond.de) will support climate adaptations via subventions, but it will not reward achievements by landowners in terms of climate change mitigation (Haertel, 2019). In addition, if more forest land was taken out of management, the demand for forest products would have to be met in other ways, perhaps with unintended consequences for the net carbon balance at continental or global scale (Hirschberger, 2008; Schulze, Frör, & Hessenmöller, 2016; Weingarten et al., 2016). Sathre and O'Connor (2010) gave a comprehensive summary of climate change mitigation options for forestry, for good reasons without referring to the non-management option.

In addition to carbon storage in forest ecosystems and harvested wood products, using wood to substitute fossil fuel-intensive-materials (product substitution) can have substantial climate benefits. However, the quantification of this substitution effect is complicated and includes various unresolved uncertainties (Leskinen et al., 2018). Therefore, only energy substitution is considered in this paper.

In the following, we would like to quantify the climate change mitigation effects of sustainably managed forests in Central Europe, considering the whole range of uses including energy production, and we will compare such a comprehensively calculated mitigation effect with the option of "no management."

## 2 | MATERIALS AND METHODS

This study is based on data from Germany, the Czech Republic, and Slovakia. We use carbon stocks and removals of managed forest from the German National Forest Inventory (BMEL, 2014; BWI-3, 2012) and carbon stocks of unmanaged forests from studies in the Czech Republic and Slovakia (Korpel, 1995). Taking forests out of management has a long history in former Czechoslovakia where forest reserves were established as early as 1895. Korpel (1995) carried out repeated inventories between 1955 and 1983 based on 60–100 m long transects in a range of forest reserves, spanning from lowland forests to the alpine region.

Storage of carbon occurs as a result of an increase in total ecosystem carbon pools of forests and wood products. Here, we address the aboveground biomass of solid stem wood with diameter ≥7 cm. In addition to storage of wood in the forest and products, wood is used for energy. We may distinguish between primary energy as firewood in households (billets) or in industrial installations, and secondary energy from sawdust and shavings generated during wood processing, and tertiary energy, which consumes products after a cascaded use. Here, we lump secondary and tertiary use of wood for energy.

Following harvest, wood may enter into a processing chain of wood industries that deliver a variety of wood products with different lifetimes and which usually uses fossil fuel for processing. At present, there is an increase in the production of wood products and associated energy of about 1.5% in industrial nations (see IPCC-SRCCL, 2019), which is in part due to replacement of non-woody products, but also due to increased consumption of existing products, traditionally produced of wood.

The product pool is transient (Schulze et al., 2019). Fresh wood enters into products and products move out of use being dumped as waste or used for energy. Following a period of use, products may also be recycled for other products, which generally have a shorter life span compared to the previous product. Based on the lifetime of short-, medium-, and long-lived products and their cascade use (Table S1; Wördehoff, Spellmann, Evers, & Nagel, 2011), the half-life of all aggregated product pools was calculated as the median of their transit time distribution. Aggregated product pools include saw wood, particle boards, and paper. The lifetimes of products were used to build a matrix of product decay rates and transfers among product classes following the framework for compartmental systems described in Metzler and Sierra (2018). The proportional allocation of harvested wood to different product classes was then used to build a vector of carbon inputs to the different product classes. The matrix of decay rates and the vector of inputs were subsequently used to compute the transit time distribution of forest products using the equations in Metzler and Sierra (2018). This transit time distribution characterizes the time carbon remains in forest products until it is released back to the atmosphere. The median of the distribution characterizes the half-life of products.

Following Döring, Glasenapp, and Mantau (2016), we assume that 50% of the products are used for energy. There will always be some products that decay naturally (e.g., a fence pole), in the same way as dead biomass in unmanaged forests. Energy substitution is the amount of fossil fuel that is replaced by energy generation from biomass, in this case from wood. It is estimated by two assumptions namely that wood is used for heating only, replacing, for example, diesel for heating, or that wood is used for production of electricity, based on a mix of fossil fuels (BAFA, 2019). The fossil fuel demand during harvest and processing of wood follows Rüter and Diederichs (2012). The fossil fuel demand for commercial harvesting was separately estimated from harvesting companies.

# 3 | RESULTS

## 3.1 | Managed versus unmanaged forest

The "life cycle" of wood under unmanaged forest conditions with a cohort of even-aged regenerating trees is used as baseline (Figure 1), assuming that also a primeval forest in the temperate zone consist of such cohorts regenerating in smaller gaps or after major disturbances (Korpel, 1995). Following a regeneration stage, there is a period of increasing stand growth and an "optimal stage" where stand volumes reach a maximum, which is followed by a "decaying stage," where various disturbances (wind throw, insects, fungal rot, etc.) may be the ultimate cause of death of trees under unmanaged conditions. In the decaying stage, stand volumes of living trees decrease and dead wood volumes increase. Thus, the carbon content of the ecosystem may fluctuate less than that of stand volumes.

The life cycles of *Fagus*- and *Picea*-dominated forests, representing the dominant forest types in Europe (Forest Europe, 2015), differ mainly with respect to total duration of their cycle. Under unmanaged conditions, *Fagus sylvatica* completes its life cycle after approximately 230 years while the life cycle of *Picea* forest may last about 350 years (Korpel, 1995). These life cycles are based on past climates, and they may be too optimistic considering future climate change induced increases in storm intensities, drought events, and diseases, as recently evidenced (Schelhaas, Nabuurs, & Schuck, 2003; Schulze, 2018; Weller, Weber, Weber, & Schulze, 2019).

The decrease in living wood volumes in the decay phase is associated with an increase in dead wood volumes, which decay approximately exponentially over time (Kahl et al., 2017; Rock, Badeck, & Harmon, 2008). Generally, regeneration overlaps with the decay phase by about 60–80 years in

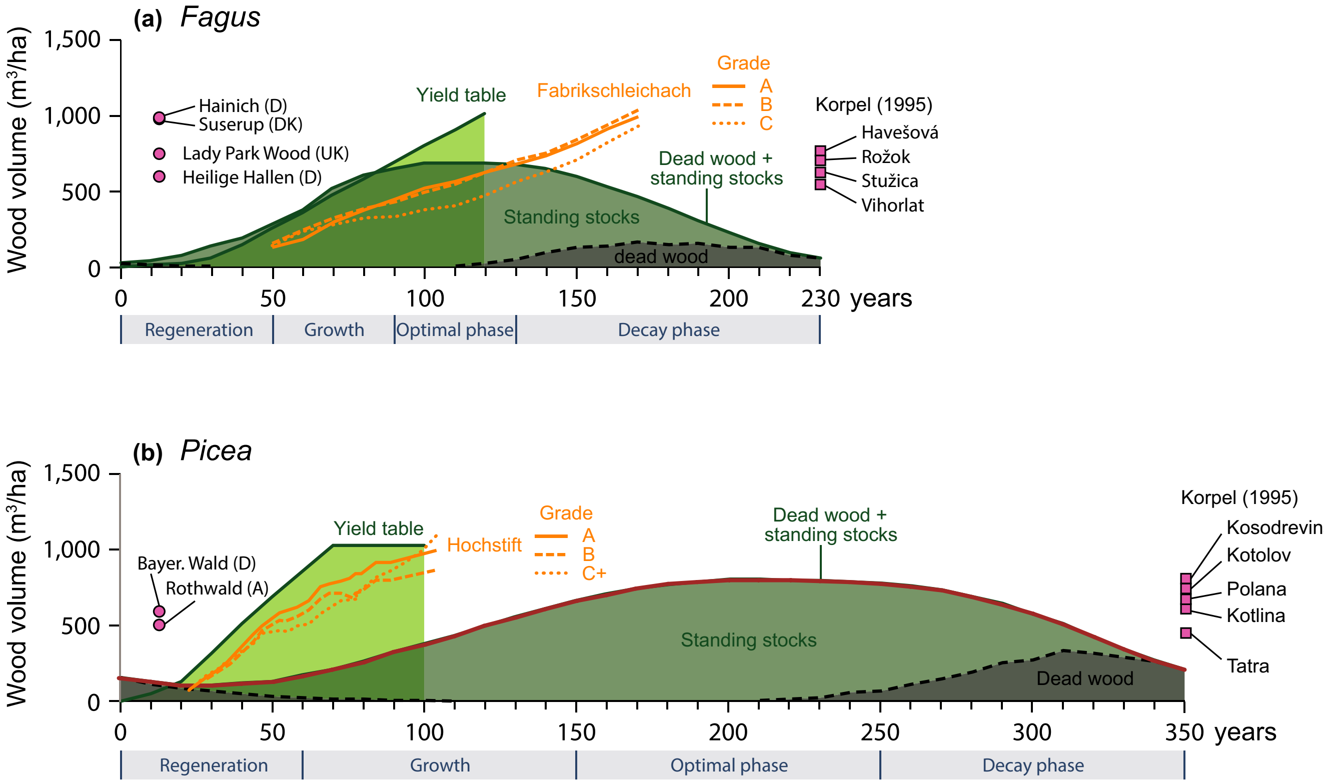

**FIGURE 1** Averages of aboveground volumes of solid wood (diameter >7 cm) in an unmanaged stand of beech (a: Korpel, 1995) and spruce (b: Korpel, 1995) at different stages of stand development, and averages of wood volumes of the individual observation plots (Korpel, 1995), and wood volumes of other sites that are under nature conservation without wood extraction in Europe (Blome, 2011; Pauer, 2016). Also, the development of stand wood volumes based on yield tables (Dittmar et al., 1983; Wenk et al., 1984) and stand development of the long-term thinning experiments are included (beech: Fabrikschleichach; Pretzsch, 2004, spruce: Hochstift; Blome, 2011) where grades A, B, and C classify thinning at low, medium, and strong thinning grades, respectively. C+ in spruce is a treatment where two-thirds of the individuals were removed in first thinning at an age of 19 years

*Fagus* and in *Picea*. Thus, even-aged “monocultures” may emerge for about 80 years in *Fagus* and about 150 years in *Picea* even under unmanaged conditions (Korpel, 1995).

In managed deciduous forests, the human induced regeneration develops very similar to that of unmanaged forests (Figure 1), because dense layers of regeneration are used for natural pruning. Only at a later stage, high quality trees are selected and promoted by thinning. The early stages of development are different for managed coniferous forests, where early tending and thinning enhance stand growth compared to unmanaged conditions.

The maximum and average stand volumes of a single age cohort are similarly in magnitude under managed and unmanaged conditions (Table 1), even though the average rotation length is about twice as high under unmanaged conditions in *Fagus* and about three times as high in unmanaged Picea forests (see also Table S2). Thus, we cannot see a “carbon debt” of management as suggested by Holtsmark (2012). The rotation cycle and half-life of trees and deadwood pools under unmanaged conditions is longer than the half-life of trees in managed stands and that of products for *Fagus*, but life-times are very similar for *Picea*. Generally, the lifetime of deadwood and of products is longer for the conifer *Picea* than for the hardwood *Fagus* (Kahl et al., 2017).

## 3.2 | Carbon accounting for climate change mitigation

Annual wood growth is the only input into the forest-wood product chain apart from fuel to produce them (Table 2). In Germany, the wood volumes of growing stocks presently increase by about 1% per year due to a left-skewed age-class distribution (BWI-3, 2012) with the largest part of forest area consisting of 60–80 year old stands (WWII cuttings). Part of the standing biomass will die by natural processes of self-thinning and remain on site. Also, early successional soft woods are cut and left on site during tending. In managed forests, there is also slash, which is generally estimated to be about 20% of the fellings, which quantifies the biomass of cut trees. This number overestimates the amount of biomass that remains on site, because bark and oversize of stem wood and industrial wood is not included in German

**TABLE 1** Average and maximum stand volumes, annual changes in volume, and half-life of wood products in managed and unmanaged deciduous and coniferous forests based on data of BMEL (2014), Schulze et al. (2019), and Korpel (1995; see Supporting Information)

| | **Fagus forest** | | **Picea forest** | |
|---|---|---|---|---|
| | **Unmanaged** | **Managed** | **Unmanaged** | **Managed** |
| Average stand volume ($m^3$/ha life and dead wood) | 381[a] to 500[b] | 399 ± 3% | 494[a] to 550[b] | 451 ± 3% |
| Maximum stand volume ($m^3$/ha life and dead wood) | 747 | 876 | 624 | 757 |
| Change in wood volume (increment; $m^3\ ha^{-1}\ year^{-1}$) | 4 | 10 | 2 | 15 |
| Half-life of a rotation (years) | 115 | 60 | 175 | 50 |
| Half-life of dead wood products (years) | 11 | 3 | 24 | 20 |

[a] Average of a single age cohort.

[b] Average of a multi-age cohort (Korpel, 1995).

statistics for wood removals. Other usable wood and even branches are sold to self-employed workers as firewood for households. Thus, a conservative estimate of the slash that remains on site is about 10% of the fellings. The amount of wood that is removed from forests reaches an estimated total of 7.91 $m^3\ ha^{-1}\ year^{-1}$ in Germany between 2002 and 2012 which is higher than previous estimates (Henning, Schnell, & Riedel, 2019). It consists of wood that is removed and used by wood industries (5.16 $m^3\ ha^{-1}\ year^{-1}$), and on wood that is sold but not recorded (bark and oversize: 0.93 $m^3\ ha^{-1}\ year^{-1}$), and on wood that is harvested for heating mainly by small land owners or self-employed workers (1.82 $m^3\ ha^{-1}\ year^{-1}$). Jochem, Weimar, Bösch, Mantau, and Dieter (2015) estimated that the additional fellings of wood for primary energy would increase the official statistics of removals of industrially used wood by about 20%–30%. The difference between firewood reported by nations to the Food and Agricultural Organization, FAO, and actual use of firewood is huge. Germany reported 10.2 mill $m^3$ fuelwood to the FAO (http://www.fao.org/faostat/en#data/FO, checked 2019), while internal reports document >20 mill $m^3$ of household firewood use annually (Döring et al., 2016). The total wood extraction from forests reaches about 70% of the annual growth. If left in the forest, this pool would decompose to $CO_2$ naturally and be released to the atmosphere as $CO_2$ with a half-life time similar to that of wood decomposition in unmanaged forest (Rock et al., 2008; Wirth et al., 2004; Table 1) as part of the natural C-cycle.

The wood balance indicates that the main difference between the natural and the human-induced C-cycle results from the use of the energy contained in wood that may substitute fossil fuel-derived energy. Since energy from wood is mainly used for heat production, it would typically substitute heating oil (diesel) in rural areas of Germany, but it may also be used for electricity and heat production in power stations. Thus, substitution of an energy mix was also quantified (BAFA, 2019). Not all wood products are used for energy, for example, fence poles. Also, harvest, transport, and production processes of wood industries require energy that typically originates from fossil fuel. This fossil fuel consumption needs to be taken into account in an energy and carbon balance. The main fraction of this processing energy is used in the wood industry. Harvesting and forwarding the wood to a transport road requires about 0.3%–0.7% of the harvested carbon-equivalent (Forstservice Beetz and Forestservice Baldauf, personal communication; Weiss, 2002).

In total, the amount of wood that is eventually used for energy production can be converted into diesel-equivalents based on the energy content in wood and in diesel or in an energy mix. The 5.33 $m^3_{wood}\ ha^{-1}\ year^{-1}$ that is available for substitution corresponds to about 0.87 $m^3_{diesel}\ ha^{-1}\ year^{-1}$ taking the fossil fuel needs for production into account (Table 2). This results in a net saving of 1.93 t $CO_{2\text{-equiv.}}\ ha^{-1}\ year^{-1}$, when accounting also for the efficiency of energy conversion. If wood is used to substitute the assumed energy mix, the $CO_2$-equivalent emission savings would be 2.15 t $CO_{2\text{-equiv.}}\ ha^{-1}\ year^{-1}$. Quantifying the total climate change mitigation effect of managed forest, the change in stocks should be added. The total climate change mitigation effect would be the sum of stock changes plus savings from energy substitution, amounting to a range of savings from 3.22 to 3.45 t $CO_{2\text{-equiv.}}\ ha^{-1}\ year^{-1}$.

We were not able to quantify the energy substitution of products (product substitution) due to a lack of data (IPCC-SRCCL, 2019). Since the product pool of wood of industrialized nations increases by about 1.5% annually (IPCC Guidelines, 2006), it is likely that there will be an ongoing substitution of fuel-intensive materials with wood besides an increasing consumption of existing wood products. However, information is lacking on the degree to which product substitution takes place (Hafner & Schäfer, 2017; Sathre & Gustavsson, 2009).

Visualizing the allocation of forest growth into different components (Figure 2) shows that a larger fraction of wood

**TABLE 2** Growth, allocation, product use, and fossil CO$_2$ emission savings by energy use of wood, taking the German national wood flow as example

| **Forest stocks and growth** | **Value** | | **Source** | **Remark** | **CO$_2$-equiv. (t CO$_2$ ha$^{-1}$ year$^{-1}$)** |
|---|---|---|---|---|---|
| | **(Mm$^3$/year)** | **(m$^3$ ha$^{-1}$ year$^{-1}$)** | | | |
| *Basic data* | | | | | |
| Forest area of Germany | 10.85 | | BMEL (2014, p. 7) | | |
| Annual wood growth | 121.60 | | BMEL (2014, p. 35) | | |
| Increment of stocks | 15.30 | | BMEL (2014, p. 35) | | |
| Dead wood | 10.40 | | BMEL (2014, p. 35) | | |
| Slash (minus bark) | 10.10 | | BMEL (2014, p. 35) | | |
| Removals | 85.80 | | | | |
| Bark and oversize | 10.10 | | Mueller (1959) | | |
| Firewood billets in 2014 | 19.70 | | Döring et al. (2016) | | |
| Wood for products | 56.00 | | Weimar (2016) | | |
| *Growth* | | | | | |
| Annual wood growth | | 11.21 | BMEL (2014, p. 33) | Annual wood growth/forest area | |
| Increment of stocks | | 1.41 | BMEL (2014, p. 35) | Increment of stocks/forest area | **1.29** |
| Dead wood production | | 0.96 | BMEL (2014, p. 35) | Deadwood/forest area | |
| Slash | | 0.93 | BMEL (2014, p. 35) | Slash—bark and oversize/forest area | |
| Removals | | 7.91 | | | |
| Bark and oversize | | 0.93 | Mueller (1959) | Bark and oversize/forest area | |
| Firewood billets in 2014 | | 1.82 | Döring et al. (2016) | Firewood/forest area | |
| Wood for products | | 5.16 | Weimar (2016) | Wood for products/forest area | |
| *Products and substitution* | | | | | |
| Material and energy replacing non-woody products | | Uncertain | | | |

| **Energy substitution from wood** | **Value** | | **Source** | **Remark** | **CO$_2$-equiv. (t CO$_2$ ha$^{-1}$ year$^{-1}$)** |
|---|---|---|---|---|---|
| | **(m$^3_{wood}$ ha$^{-1}$ year$^{-1}$)** | **(Mwh ha$^{-1}$ year$^{-1}$)** | | | |
| Decomposition of products | 2.58 | 5.16 | Döring et al. (2016) | 50% of products decompose | |
| Total wood use for energy | 5.33 | 10.66 | | Energy use of products + bark + firewood | 4.88 |
| Energy use of products | 2.58 | 5.16 | Döring et al. (2016) | 50% of products are used for energy | 2.37 |
| Bark and oversize (shavings) | 0.93 | 1.86 | | | |
| Firewood billets | 1.82 | 3.63 | Döring et al. (2016) | | |
| Fossil fuel consumption for harvest and production | 1.00 | 2.00 | Rüter and Diederichs (2012) | Value is equal to energy content of 1 m$^3_{wood}$ ha$^{-1}$ year$^{-1}$ = 0.92 t CO$_2$ eq. | 0.92 |
| Wood for energy minus energy used for production | 4.33 | 8.66 | | Total wood use for energy − fossil fuel consumption for production | 3.97 |
| *Wood for energy including conversion losses* | 3.68 | 7.36 | | Wood use for energy − fossil fuel for production × efficiency of heat and power cogeneration (CHP) | 3.37 |

(Continues)

**TABLE 2** (Continued)

| Fossil fuel substitution | Value |  | Source | Remark | $CO_2$-equiv. (t $CO_2$ $ha^{-1}$ $year^{-1}$) |
|---|---|---|---|---|---|
|  | ($m^3_{diesel}$ $ha^{-1}$ $year^{-1}$) | (Mwh $ha^{-1}$ $year^{-1}$) |  |  |  |
| Gross substitution of diesel | 1.07 | 10.66 | BDEW (2017) | Total wood use for energy × energy content wood)/energy content diesel | 2.79 |
| Fossil fuel consumption for harvest and production | 0.20 | 2.00 | Rüter and Diederichs (2012) | Value is equal to energy content of 1 $m^3_{wood}$ $ha^{-1}$ $year^{-1}$ = 0.92 t $CO_2$ eq. | 0.92 |
| Energy substitution of diesel | 0.87 | 8.66 |  | Net energy substitution × $CO_2$ emission per $m^3$ diesel | 2.27 |
| ***Net energy substitution diesel/heating oil*** |  | 7.36 |  | Net usable energy content of wood × $CO_2$ emission per $m^3$ diesel × efficiency of CHP | **1.93** |
| ***Net energy substitution CHP*** |  | 7.36 |  | Net usable energy content of wood × energy content wood × efficiency CHP × emission factors | **2.15** |
| ***Total climate mitigation of managed forest*** | 6.74 |  |  | Increment of stocks ($CO_2$ eq.) + net energy substitution diesel ($CO_2$ eq.) | **3.22** |
|  |  |  |  | Increment of stocks ($CO_2$ eq.) + net energy substitution CHP use ($CO_2$ eq.) | **3.45** |
| ***Total climate mitigation of unmanaged forest (Hainich)*** |  |  |  |  |  |
| Increment of stocks | 0.40 |  | Hainich (2015) |  | 0.37 |
| ***Additional Information*** |  |  |  |  |  |
| Energy content wood |  |  | BDEW (2017) | (MJ/$m^3$) | 7,200 |
| Energy content wood |  |  | BDEW (2017) | (kWh/$m^3$) | 2,000 |
| Energy content diesel |  |  | BDEW (2017) | (MJ/$m^3$) | 36,000 |
| $CO_2$ emission per $m^3$ diesel |  |  | BDEW (2017) | (t $CO_2$) | 2.62 |
| Conversion from $X$ $m^3$ into $CO_2$-equivalents |  |  | Mueller (1959) | $X/4 \times 44/12$ |  |
| Efficiency heat–power cogeneration (CHP) reference value |  |  | European Biomass Association (AEBIOM, 2015) | % | 88.00 |
| Electricity generation |  |  | AEBIOM (2015) | % | 18.00 |
| Heat generation |  |  | AEBIOM (2015) | % | 70.00 |
| Emission factor of the electricity mix of Germany |  |  | Bundesamt für Wirtschaft und Ausfuhrkontrolle 2019 (BAFA) | (kg $CO_2$ eq./kWh) | 0.54 |
| Emission factor of heat generation |  |  | BAFA (2019) | (kg $CO_2$ eq./kWh) | 0.28 |

growth enters into primary bioenergy (billets and bark) than into the increment of stocks and dead wood. Less than 50% of growth enters into the product pool. Since only half of the products are used for energy production by the end of their life, about 50% of growth is eventually used for bioenergy. Therefore, billets and bark contribute more to bioenergy than discarded products. Since fire wood is mainly used by small properties in rural areas, small land-owners are significant contributors to climate change mitigation. However, Figure 2 also indicates that there is an upper limit to energy generation by biomass from sustainably managed forests (Schulze, Körner, Law, Haberland, & Luyssaert, 2012).

In unmanaged forests, the increase in stocks is the only process that contributes to climate change mitigation, and the long-term net increment in stocks would be zero in the long term both in sustainably managed and

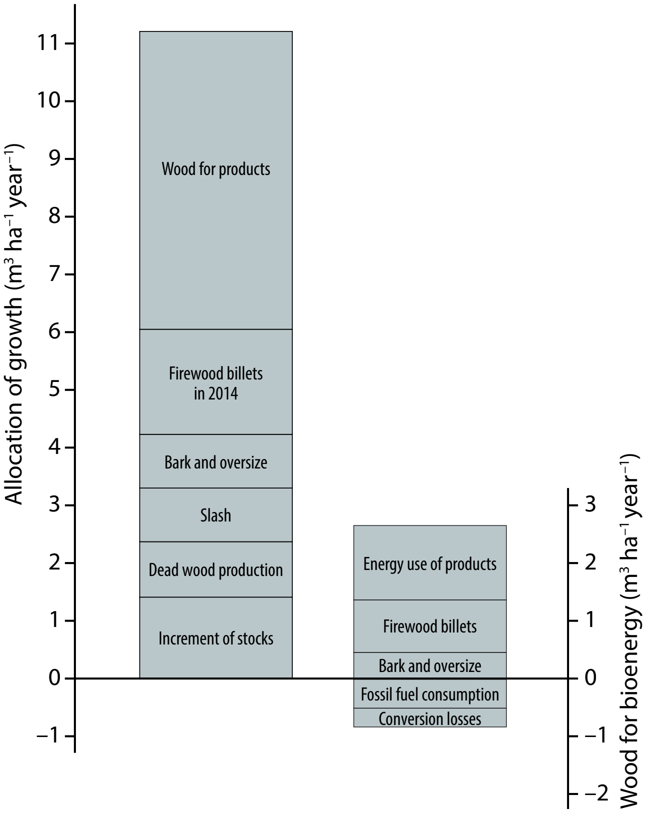

**FIGURE 2** The allocation of growth into different components (left column), and the origin of wood used for bioenergy (right column)

under unmanaged conditions in the absence of disturbances. Taking the National Park of Hainich as an example, repeated inventories show an increase in stocks of 0.4 $m^3$ $ha^{-1}$ $year^{-1}$ (Hainich, 2015). This would be equivalent to 0.37 t $CO_2$ $ha^{-1}$ $year^{-1}$, which is about 10% of the mitigation effect of commercially managed forest.

## 4 | DISCUSSION

In this study, we show that the regional climate change mitigation potential of sustainably managed forests is about 10 times as high as that of forests taken out of management, based on the lifetime of trees under unmanaged conditions. The difference is mainly due to the substitution effect from the use of discarded wood products as feedstock for bioenergy. Compared to the mitigation effect of bioenergy, the mitigation effect of increasing carbon stocks in the forest ecosystem is small (Table 2; 63%). Old-growth European forests and forests taken out of management may not even have such a potential in the near future, if they are currently at their maximum stocks.

The area-averaged stand volumes did not significantly differ between unmanaged and managed forests in Europe. This may be different in other regions of the world, where higher stand volumes can be reached over longer periods of time, such as in the Pacific Northwest of North America (Hudiburg et al., 2009) or in Tasmania (Keith, Mackey, & Lindenmayer, 2009). The European main tree species (*F. sylvatica* and *Picea abies*) do not get very old, even in protected forest areas. For *Fagus*, it is mainly the attack by fungi that lead to rotting of the hardwood (Schulze, 2017). In *Picea*, it is mainly wind throw that terminates the life of this shallow-rooted species. Generally, wind throw is followed by bark beetle outbreaks that emerge with a 70–100 year interval in both North America (Nikiforuk, 2011) and Europe (Weller et al., 2019). Bark beetle outbreaks may additionally emerge after drought without wind throw. Thus, for protected areas of old-growth forest, the release of carbon by decomposition is close to the sequestration rate by photosynthesis, neglecting the small amount of carbon that enters into soils in the long term (Schrumpf, Schumacher, Schoening, & Schulze, 2008). Carbon storage in soils seems to be of the same magnitude in managed and unmanaged forest, mainly because of modern harvesting techniques that leave major parts of a forest free from traffic of harvesting machines, as they operate on prescribed permanent tracks (I. Schöning, personal communication). However, since aboveground wood and carbon are being removed under management conditions, we cannot exclude differences in soil carbon pools that may develop over the long term (C. A. Sierra, submitted).

One major difference between managed and unmanaged forest is the supply of wood to a product pool (Figure 3). This product pool is transient, because wood enters into this pool, and leaves it again after usage. Thus, the total carbon pool in products is almost constant, or shows minor oscillations with the harvesting cycle (Schulze et al., 2019). The additional accounting of the product pool, as proposed by the Paris Agreement, and the associated stock taking, does not reveal the total climate change mitigation capacities of forest management. A cascaded use of wood products will likely not change this situation (Table S1). The lifetime of sequestered carbon increases in cascaded use and reuse, but the postponement of the emissions is likely only a few years, because reuse tends to turn long-lived products into short-lived products. This may change in the future, if fossil fuel-based products (plastics) are replaced by long-lived bioproducts (WBW, 2018). Figure 3 also reveals that the fraction of photosynthesis that enters into products and energy is fairly small (4.1%). In the product part of the carbon cycle solid wood is handed from the forest to wood industries and from there to the energy-producing facilities. Emissions of photosynthetically bound $CO_2$ occur eventual from decomposition of products or from energy production at the terminal end of usage.

Our results confirm earlier model studies on GHG dynamics in forests and wood products. Werner, Taverna, Hofer, Thürig, and Kaufmann (2009) showed for Switzerland that only the forest management scenario led to a climate change mitigation effect in the long term. Reduced management

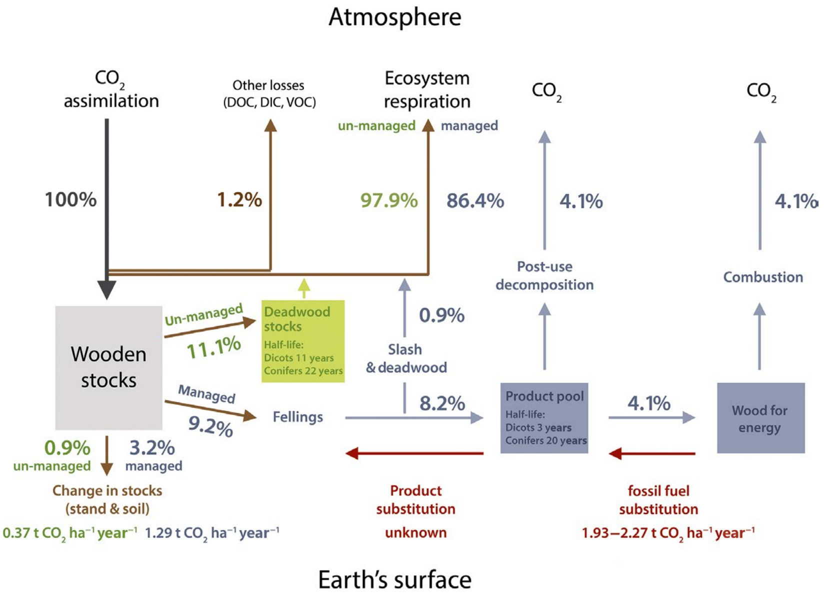

**FIGURE 3** Carbon flows in managed and unmanaged forest. Numbers indicate the fraction of $CO_2$ assimilation as baseline (100%)

resulted in larger net emissions. However, our results contrast of those of Harmon, Ferrell, and Franklin (1990) who assumed much lower efficiencies in the conversion of harvested wood to long-lived products and bioenergy. Therefore, the role of forests for climate change mitigation may depend on regional differences in how forests are managed and wood is used, and the specific accounting methodologies (e.g., Chen, Ter-Mikaelian, Yang, & Colombo, 2018).

The major effect of the wood flow in the economic system is the final use of the energy embedded in wood products, which can be used as bioenergy, substituting fossil fuels. In modern energy systems that are based on renewable energy production, energy from biomass will have a buffering role for renewable energy from sources that fluctuate. Presently, about 50% of the product pool is used for bioenergy in Germany (Döring et al., 2016). It might be possible to increase this fraction in the future, but it will remain impossible to recover all products.

For reporting purposes, the climate change mitigation effect of generating bioenergy is accounted for in the energy sector, and not in the forest sector (IPCC Guidelines, 2006). Also, it is the industrial sector and not forestry that receives the credits for possible increases in the product pool and mitigation from substitution of fossil fuel-intensive products. Thus, the climate change mitigation debate in forestry is centered around the question of how to increase the carbon stocks (Riedel, Stürmer, Hennig, Dunger, & Bolte, 2017), neglecting the fact, that the terminal product of wood is energy. Also, fast rotation leads to an increase in fossil fuel substitution, and possibly to an increase in the wood product pool. In *Picea*, the managed forest has two to three life cycles in the time of one life cycle of unmanaged forests. However, it is the accumulated amount of saved emissions from substituted fossil fuel in a comparable timeframe that should count in the mitigation debate (Schulze et al., 2019). Harvest in the framework of sustained forestry is not an emission, but the basis for substitution of fossil fuels and more fossil-intensive materials. Only, in the context of land-use change, deforestation is an emission. Thus, forestry should sell wood in units of fossil fuel substitution, and this should be credited to forestry, and this could justify payments to the owner. It also would provide an incentive for increasing forest productivity and not only of forest stocks, and avoid misunderstandings in carbon balances (Grassi, Pilli, House, Federici, & Kurz, 2018).

For unmanaged forests, the contribution to climate change mitigation through storage is very small or close to nil. The contribution to fossil fuel substitution is lacking. This should justify a carbon and energy cost for taking forest out of management. In contrast, the energy substitution by forest management per area used is only about 4% of the power generation by wind turbines based on 420 m distance between 1.5 MW-turbines and 20% efficiency as in Germer and Kleidon (2019), and less than 0.1% of the power generated by solar panels per used area. Thus, there will be a competition for the use of land in the future, in consideration that forests provide additional benefits to society.

It becomes clear that adding an accounting system for carbon storage in wood products into the forest accounting scheme has reduced the bias between unmanaged and managed forests, but this extension is not sufficient. The accounting of producing wood for energy generation and fossil fuel substitution remains invisible, as well as the effect from substituting fossil fuel-intensive materials and products with less fossil fuel-intensive wood and wood products.

## 5 | IS THERE A SOLUTION?

The zero accounting of bioenergy by the energy industries was intended to avoid double accounting of emissions. However, the forest sector should also be rewarded for its efforts to sustainably managing their forests in a changing world and the following suggestions should be considered.

- Sustainable harvesting should not be accounted as emission in the forest sector, because the wood that enters into a product chain is part of the natural carbon cycle (it originates from photosynthesis), where the half-lives of decomposition processes after natural mortality and of harvested wood are very similar. However, this approach can be criticized for not accounting real emissions that take place in combustion. The nature of the carbon cycle suggests that accounting of carbon emissions from resources of recent biogenic origin should be left out.
- In the future, the emissions from energy production based on fossil fuel could pay a $CO_2$ tax. It is the political intention that the $CO_2$ tax should be returned to the public. In the case of bioenergy, the $CO_2$ tax could potentially be used to reward the forest owners, who facilitated a supply of this sustainable and renewable resource and thus contributed to climate change mitigation.

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## REFERENCES

AEBIOM. (2015). *Report on conversion efficiency of biomass*, Version 2 (pp. 1–21). Brussels, Belgium: European Biomass Association.

BAFA. (2019). *Merkblatt zu den $CO_2$-Faktoren*. Eschborn, Germany: Bundesamt für Wirtschaft und Ausfuhrkontrolle, 4 pp.

BDEW. (2017). *Erdgas. Zahlen, Daten Fakten*. Berlin, Germany: Bundesverband der Energie und Wasserwirtschaft, 24 pp.

Blome, R. (2011). *Ertragskundliche Auswertung des Fichtendurchforstungsversuchs Hochstift 990 B unter Berücksichtigung qualitätsbeeinflussender Wuchsmerkmale*. Unpublished Master thesis, University of Göttingen, p. 19.

BMEL. (2014). *Der Wald in Deutschland: Ausgewählte Ergebnisse der dritten*. Berlin, Germany: Bundeswaldinventur, 50 pp.

Bouriaud, O., Don, A., Janssens, I. A., Marin, G., & Schulze, E. D. (2019). Effects of forest management on biomass stocks in Romanian beech forests. *Forest Ecosystems*, *6*. https://doi.org/10.1186/s40663-019-9180.4

Bouriaud, O., Marin, G., Bouriaud, L., Hessenmöller, D., & Schulze, E. D. (2016). Romanian legal management rules limit wood production in Norway spruce and beech forests. *Forst Ecosystems*, *3*, 20. https://doi.org/10.1186/s40663-016-0079-2

Burschel, P., & Huss, J. (2003). *Grundriss des Waldbaus*. Stuttgart, Germany: Ulmer Verlag, 485 pp.

BWI-3. (2012). Bundeswaldinventur. Retrieved from https://www.bundeswaldinventur.de/

Chen, J., Ter-Mikaelian, M. T., Yang, H., & Colombo, S. J. (2018). Assessing the greenhouse effects of harvested wood products manufactured from managed forests in Canada. *Forestry*, *91*, 193–205. https://doi.org/10.1093/forestry/cpx056

Ciais, P., Schelhaas, M. J., Zaehle, S., Piao, S. L., Cescatti, A., Liski, J., … Nabuurs, G. J. (2008). Carbon accumulation in European forests. *Nature Geoscience*, *1*, 425–429. https://doi.org/10.1038/ngeo233

Dittmar, O., Knapp, E., & Lembcke, G. (1983). *DDR-Buchenertragstafe*. Eberswalde, Germany: Institut für Forstwissenschaften, Abteilung Information, 57 pp.

Döring, P., Glasenapp, S., & Mantau, U. (2016). Energieholzverwendung in privaten Haushalten 2014. In U. Mantau, P. Döring, H. Weimar, & S. Glasnapp (Eds.), *Rohstoffmonitoring Holz. Mengenmäßige Erfassung und Bilanzierung der Holzverwendung in Deutschland. Schriftenreihe Nachwachsende Rohstoffe*, *38*, 5–37.

EEG. (2003). Gesetz für den Vorrang erneuerbarer Energien (Erneuerbare-Energie-Gesetz-EEG) from 29.3.2000, revised 22.12.2003. Bundesgesetzblatt, p. 305. Retrieved from http://www.clearingstelle-eeg-kwkg.de

Forest Europe. (2015). *State of Europe's forests*. Madrid, Spain: Ministerial Conference on the Protection of Forests in Europe, Forest Europe Liaison Unit Madrid, 314 pp.

Germer, S., & Kleidon, A. (2019). Have wind turbines generated electricity as would be expected from the prevailing wind conditions in 2000–2014? *PLoS ONE*, *14*, e0211028. https://doi.org/10.1371/journal.pone.0211028

Grassi, G., Pilli, R., House, J., Federici, S., & Kurz, W. A. (2018). Science-based approach for credible accounting of mitigation in managed forests. *Carbon Balance and Management*, *13*, 16. https://doi.org/10.1186/s13021-018-0096-2

Greenpeace. (2018). *Wenn Wälder wieder wachsen. Eine Waldvision für Klima, Mensch und Natur*. Based on a study by the Öko-Institut. Freiburg, Germany: Öko-Institut, 11 pp.

Haertel, I. (2019). Eigentumsgarantie und Waldrecht. In O. Depenheuer & B. Moehring (Eds.), *Waldeigentum* (pp. 165–196). Heidelberg, Germany: Springer Verlag.

Hafner, A., & Schäfer, S. (2017). Environmental aspects of material efficiency versus carbon storage in timber buildings. *European Journal of Wood and Wood Products*. https://doi.org/10.1007/s00107-017-1273-9

Hainich, N. P. (2015). Waldentwicklung im Nationalpark Heinich: Ergebnisse der ersten Wiederholung der Waldbiotopkartierung, Waldinventur und der Aufnahme der vegetationskundlichen Dauerbeobachtungsflächen. *Erforschen*, *3*, 1–70.

Harmon, M. E., Ferrell, W. K., & Franklin, J. F. (1990). Effects of carbon storage of conversion of old growth forests to young forests. *Science*, *247*, 699–702. https://doi.org/10.1126/science.247.4943.699

Henning, P., Schnell, S., & Riedel, T. (2019). Rohstoffquelle Wald – Holzvorrat auf neuem Rekord. *AFZ-DerWald*, *14*(2019), 24–27.

Hirschberger, P. (2008). *Illegaler Holzeinschlag und Deutschland; eine Analyse der Außenhandelsdaten*. Frankfurt am Main, Germany: WWF Deutschland.

Holtsmark, B. (2012). Harvesting in boreal forests and the biofuel carbon debt. *Climatic Change*, *112*, 415–428. https://doi.org/10.1007/s10584-011-0222-6

Hudiburg, T., Law, B., Turner, D. P., Campbell, J., Donato, D., & Duane, M. (2009). Carbon dynamics of Oregon and Northern California forest and potential land-based carbon storage. *Ecological Applications*, *19*, 163–180. https://doi.org/10.1890/07-2006.1

IPCC. (2013). *Climate change 2013: The physical basis. Contribution of working group I to the 5th assessment report of the Intergovernmental Panel of Climate Change*. Cambridge, UK: Cambridge University Press, 1535 pp.

IPCC Guidelines. (2006). *IPCC guidelines for national greenhouse gas inventories*. Retrieved from https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html

IPCC-SRCCL. (2019). *Climate change and land*. Retrieved from https://www.ipcc.ch/report/srccl/

Jochem, D., Weimar, H., Bösch, M., Mantau, U., & Dieter, M. (2015). Estimation of wood removals and fellings in Germany: A calculation approach based on the amount of used roundwood. *European Journal of Forest Research*, *134*, 869–888. https://doi.org/10.1007/s10342-015-0896-9

Kahl, T., Arnstadt, T., Baber, K., Bässler, C., Bauhus, J., Borken, W., … Gossner, M. M. (2017). Wood decay rates of 13 temperate tree species in relation to wood properties, enzyme activities and organismic diversity. *Forest Ecology and Management*, *391*, 86–95. https://doi.org/10.1016/j.foreco.2017.02.012

Keith, H., Mackey, B. G., & Lindenmayer, D. B. (2009). Re-evaluation of forest biomass carbon stocks and lessons from the world's most carbon dense forests. *Proceedings of the National Academy of Sciences of the United States of America*, *106*, 11635–11640. https://doi.org/10.1073/pnas.0901970106

Korpel, S. (1995). *Die Urwälder der Westkarpaten*. Stuttgart, Germany: Gustav Fischer Verlag, 310 pp.

Kramer, H. (1988). *Waldwachstumslehre*. Hamburg, Germany: Paul Parey, 374 pp.

Leskinen, P., Cardellini, G., González-García, S., Hurmekoski, E., Sathre, R., Seppälä, J., … Verkerk, P. J. (2018). Substitution effects of wood-based products in climate change mitigation. *From Science to Policy 7*. European Forest Institute, 27 pp. https://doi.org/10.36333/fs07

Metzler, H., & Sierra, C. A. (2018). Linear autonomous compartmental models as continuous-time Markov chains: Transit-time and age distributions. *Mathematical Geosciences*, *50*(1), 1–34. https://doi.org/10.1007/s11004-017-9690-1

Mueller, R. (1959). *Grundlagen der Forstwirtschaft*. Hannover, Germany: Scharper Verlag, 1257 pp.

Nikiforuk, A. (2011). *Empire of the beetle: How human folly and a tiny bug are killing North America's great forests*. Vancouver, BC, Canada: Greystone Books, 230 pp.

Pauer, G. (2016). Modelling carbon stocks of unharvested European beech forests as a baseline for calculating carbon parity times. Master thesis, University of Copenhagen, 53 pp.

Pretzsch, H. (2004). Chapter 6: Standard analysis of long-term experimental plots. In H. Pretzsch (Ed.), *Forest dynamics, growth and yield: From measurement to model* (pp. 208–210). Heidelberg, Germany: Springer Verlag.

Riedel, T., Stürmer, W., Hennig, P., Dunger, K., & Bolte, A. (2017). Wälder in Deutschland sind eine wichtige Kohlenstoffsenke. *AFZ-DerWald*, *14*, 14–18.

Rock, J., Badeck, F. W., & Harmon, M. E. (2008). Estimating decomposition rate constants for European tree species from literature sources. *European Journal of Forest Research*, *127*, 301–313. https://doi.org/10.1007/s10342-008-0206-x

Rüter, S., & Diederichs, S. (2012). Ökobilanz-Basisdaten für Bauprodukte aus Holz. Arbeitsbericht aus dem Institut für Holztechnologie und Holzbiologie 2012/1, 303 pp.

Sathre, R., & Gustavsson, L. (2009). A state-of-the-art review of energy and climate effects of wood product substitution. Ecotechnology, Mid Sweden University Ötersund.

Sathre, R., & O'Connor J. (2010). *A synthesis of research on wood products and greenhouse gas impacts*. Technical Report 19R (2nd ed.). Vancouver, BC, Canada: FPInovations, 117 pp.

Sato, A., & Nojiri, Y. (2019). Assessing the contribution of harvested wood products under greenhouse gas estimation: Accounting under the Paris Agreement and the potential for double-counting among the choice of approaches. *Carbon Balance and Management*, *14*, 15. https://doi.org/10.1186/s13021-019-0129-5

Schelhaas, M. J., Nabuurs, G. J., & Schuck, A. (2003). Natural disturbances in European forests in the 19th and 20th century. *Global Change Biology*, *9*, 1620–1633. https://doi.org/10.1046/j.1365-2486.2003.00684.x

Schrumpf, M., Schumacher, J., Schoening, I., & Schulze, E. D. (2008). Monitoring carbon stock changes in European soils: Process understanding and sampling strategies. *Ecological Studies*, *203*, 153–189. https://doi.org/10.1007/978-0-387-76570-9_9

Schulze, E. D. (2017). Biodiversität und Waldbewirtschaftung im Laubwald: *Artenschutzreport 37/2017*, 3–11.

Schulze, E. D. (2018). Effects of forest management on biodiversity in temperate deciduous forests: An overview based on Central European beech forests. *Journal of Nature Conservation*, *43*, 213–226. https://doi.org/10.1016/j.jnc.2017.08.001

Schulze, E. D., Frör, O., & Hessenmöller, D. (2016). Externe ökologische Folgen von Flächenstilllegungen im Wald. *AFZ-DerWald*, *15*, 24–26.

Schulze, E. D., Körner, C. H., Law, B., Haberland, H., & Luyssaert, S. (2012). Large-scale bioenergy from additional harvest of forest biomass is neither sustainable nor greenhouse gas neutral. *Global Change Biology – Bioenergy*, *4*, 611–616. https://doi.org/10.1111/j.1757-1707.2012.01169.x

Schulze, E. D., Luyssaert, S., Ciais, P., Freibauer, A., Janssens, I. A., Soussana, J. F., … Gash, J. H. (2009). Importance of methane and nitrous oxide for Europe's terrestrial greenhouse-gas balance. *Nature Geoscience*, *2*, 842–850. https://doi.org/10.1038/ngeo686

Schulze, E. D., Stupak, I., & Hessenmöller, D. (2019). The climate mitigation potential of managed versus unmanaged spruce and beech forests in central Europe. In J. C. M. Pires & A. L. Goncalves (Eds), *Bioenergy with carbon capture and storage: Nature and technology can help* (pp. 131–149). Antwerp, Belgium: Elsevier.

UNFCCC-COP17. (2011). *Conference of the Parties (COP17), Durban, 2011. 2/CMP.7 land use, land use change and forestry*. Retrieved from https://unfccc.int/index.php/process-and-meetings/conferences/past-conferences/durban-climate-change-conference-november-2011/cop-17

UNFCCC-COP21. (2015). Conference of the Parties (COP21) Paris, 2015. Adoption of the Paris Agreement. Proposal by the President.

*Paris Climate Change Conference – November 2015, COP 21*, 21932 (December): 32. Retrieved from http://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf

UNFCCC-COP3. (1997). *Conference of the Parties (COP3), Kyoto, 1997. Adoption of the Kyoto Protocol*. Retrieved from https://unfccc.int/process-and-meetings/conferences/past-conferences/kyoto-climate-change-conference-december-1997/cop-3

WBW. (2018). *Erhöhung der stofflichen Nutzung von Holz in gebäuden im Einklang mit der Rohstoffverfügbarkeit*. Bonn, Germany: Wissenschaftlicher Beirat für Waldwirtschaft, 11 pp.

Weimar, H. (2016). Holzbilanzen 2013 bis 2015 der Bundesrepublik Deutschland. Thünen Working Paper 57, 1–25.

Weingarten, P., Bauhus, J., Arens-Azevedo, U., Balmann, A., Biesalski, H. K., Birner, R., … Weiger, H. (2016). *Klimaschutz in der Land- und Forstwirtschaft sowie in den nachgelagerten Bereichen Ernährung und Holzverwendung*. Berichte über Landwirtschaft, Sonderheft 222. Retrieved from https://doi.org/10.12767/buel.v222il.149.g295

Weiss, B. (2002). Bilanzierung des fossilen Kohlenstoffeinsatzes bei der Produktion von Fichtenrohholz im Wuchsgebiet Baar-Wutach. Diplomarbeit, Rottenburg, Fachhochschule.

Weller, E., Weber, G. E., Weber, U., & Schulze, E. D. (2019). Zur Bewirtschaftung der Fichte. *AFZ-DerWald*, *7*, 58–61.

Wenk, G., Römisch, K., & Gerold, D. (1984). *DDR-Fichtenertragstafel*. Tharandt, Germany: Agrarwissenschaftliche Gesellschaft der Deutschen demokratischen Republik, 64 pp.

Werner, F., Taverna, R., Hofer, P., Thürig, E., & Kaufmann, E. (2009). National and global greenhouse gas dynamics of different forest management and wood use scenarios: A model-based assessment. *Environmental Science and Policy*. https://doi.org/10.1016/j.envsci.2009.10.004

Wirth, C., Schulze, E.-D., Schwalbe, G., Tomczyk, S., Weber, G., & Weller, G. (2004). Dynamik der Kohlenstoffvorräte in den Wäldern Thüringens. *Mitteilungen der Thüringer Landesanstalt für Wald, Jagd und Fischerei 23/2004*, 0-302.

Wördehoff, R., Spellmann, H., Evers, J., & Nagel, J. (2011). Kohlenstoffstudie Forst und Holz Niedersachsen. *Beiträge aus der Nordwestdeutschen Forstlichen Versuchsanstalt 6*: 0-92.

## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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