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The role of wood harvest from sustainably managed forests in the carbon cycle

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Key message: We investigate the flux balance of managed and protected forests and the effects of using wood.

- Flux parameters of CO_2 uptake and respiration do not differ between managed and protected forests.
- Accounting of harvest as immediate emission by IPCC guidelines results in a bias of forest climate mitigation towards storage and neglects the avoidance of fossil-fuel use by wood use.

Keywords: Bioenergy, Climate, Carbon cycle, Wood-use for products and energy, Carbon storage, Atmospheric carbon dioxide, Biodiversity

1 Introduction

While global emissions of radiative-forcing gasses continue to increase every year, of which carbon dioxide (over 40 Gt CO_2 year^{-1}) remains predominant (Cain et al., 2019), forests are being studied for their potential role of carbon sequestration, but also for provisioning society with renewable material and energy. Noticeably, these two roles, sequestering and provisioning, are opposed forms of mitigation strategies. Sustainable management is meant to maintain constant levels of carbon stocks including soil carbon despite of harvest while sequestration aims at increasing carbon stocks by restricting harvest. The debate about which strategy is more suitable was so far largely discussed from economic perspectives (e.g., Baker et al., 2019, Favero et al., 2020).

More recently, the EU shifted its policy towards sequestration in detriment of wood use. The underlying assumption is that forests' carbon stock can be sufficiently increased as to produce a large-scale, long-term, and stable carbon sink. However, this ignores the risk of forests becoming unstable as they age, a process that will be exacerbated by climate change (e.g., Schelhaas et al., 2013, Kruhlov et al., 2018).

Until now, it remains largely unclear whether sustainably managed forests contribute more towards climate mitigation than protected forests (Luyssaert et al., 2018; Schulze et al., 2020). The answer to this question is complicated by the fact that fossil fuel use must be included in the calculation because the use or non-use of forests has implications for the level of fossil CO_2 emissions. Here, we are dealing with sustainably managed forests where forest biomass (above and below ground living and dead biomass) at landscape scale remains constant, and not with exploitation forestry where harvest exceeds growth and biomass declines, nor with forest degradation and land-use change. Sustainability of management in forestry was defined by von Carlowitz about 300 years ago as "harvest should balance growth" (von Carlowitz, 1730). Sustainable management does not define the amount of standing wood volumes, because wood volumes depend not only on the site conditions but also on the management objectives. They will be different for coppice, for high forests, and for continuous cover forestry (Kramer, 1988). Even though the EU Forest strategy (Resende et al., 2021) has widened the definition of sustainability including also social and environmental aspects, we confine this broad definition to the aspect of forest growth including humus dynamics in the soil. Taking Germany as an example in this study,

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sustainability of forests is reached by management plans that are re-assessed every decade for properties and co-operatives that are greater than 50 ha and by certification of management by independent agencies (PEFC, FSC). We estimate that > 90% of the forest area in Germany is managed sustainably.

In managed forests, harvest takes place as tending and thinning where future trees are selected and released from competition (Savill and Evans, 2004) and as final harvest of single trees or mature stands above a ground cover of natural regeneration (Pretzsch, 2019). Tending, thinning, and harvest are actions concentrated on a fraction of the forest property (Burschel and Huss, 2003) in order to increase the growth of the stands and the quality of the stems. On a sustainably managed property, tending or harvest in a specific stand takes place once in about 5 to 10 years (Schall and Ammer, 2013). Thus, the area affected by tending or harvesting every year is about 10% of the property and this affected area moves dynamically across the property where the impact of harvest is only transitory at plot scale (Bouriaud et al., 2019). The distribution of these actions over space and time makes a comparison with fixed experimental plots of flux measurements difficult. In addition, experimental plots are often concentrated in mature forests. Thus, methodological difficulties remain in the quantification of the dominant carbon fluxes as measured by eddy covariance (Foken, 2017), because fluxes and harvest operate at different scales in space and time (Schulze et al., 2021).

In addition to the question, to what extent management or protection contributes to climate mitigation, there is an ongoing debate about using wood for energy production (Söderberg and Eckerberg, 2013). Wood has a lower energy density than fossil fuels, but it is the political aim to reduce fossil fuel emissions (see, e.g., EU, 2009). The use of harvested wood for products avoids fossil fuel use, and the carbon in wood that is used in products or for energy would otherwise be emitted by microorganisms during decomposition. Thus, combustion of fresh wood that cannot be used for products and of wood products after use is an important contribution to actively reduce fossil fuel use. Since emissions from fossil fuel use make the largest contribution of all carbon emissions, we think that any mechanism to actively reduce this component with immediate beneficial effects on climate has priority over mechanisms that compensate fossil fuel emissions, such as storage of carbon in living and dead forest biomass. Consequently, it is an additional aim of this study to explore the role of harvest and wood-use in its effects on fossil fuel use.

The land-use based climate mitigation potential of Central Europe is quite small at a high level of industrialization (Roe et al., 2020), and this potential results mainly from a strict commitment towards sustainable forest management.

Here, we use published data with a focus on Germany, due to the data availability. We compare these data with global datasets whenever possible.

Forests that are managed for wood production comprise age class forests with natural regeneration, and continuous cover forestry, where single trees are harvested when reaching certain dimensions. This contrasts to land where harvesting and wood extraction are halted, and growth contributes to increasing stand volumes and to natural decay. In Germany, about 95% of the forest area is managed, and about 5% of the area remains unmanaged (BMEL, 2015). This will change in the future, when the EU request of 30% protection of the land has been implemented (Resende et al.,, 2021).

Protected forest is mainly represented by National Parks, where all successional stages are present at landscape scale (Korpel, 1995). In Germany, data from repeated inventories were available only for Hainich National Park (Hainich, 2012). It should be kept in mind that National Parks in Europe consist of formerly managed forests or land formerly used for agriculture or military purposes. Hainich National Park was a former communal forest that was operated as coppice with standards before it became a military training area and then a National Park, which is now growing into a high forest (Hainich, 2012). The forest area increased with succession on former military installations. Untouched wilderness landscapes do neither exist in Germany nor over most of the European continent. Despite a long history of national inventories, the comparison of managed versus protected forests has very seldom been made at landscape scales (Bouriaud et al. 2019).

Our study is based mainly on flux measurements by eddy covariance (Aubinet et al., 2000) which is a micrometeorological approach, in which the flux of CO_2 into and out of an ecosystem is directly and continuously monitored at a time scale of 30 minutes. The approach is critically evaluated by Foken (2017).

2 Carbon flow and storage in the forest ecosystem

Figure 1 summarizes the carbon cycle of managed and unmanaged forest in relative terms at landscape scale, because absolute numbers depend on site conditions and legacies of the past land use (Thom et al., 2018). However, for Europe the average carbon input into forests by photosynthesis is 1107 g C m^{-2} $year^{-1}$ (Schulze et al. 2009). In Fig. 2, this value represents 100%. It remains difficult to estimate uncertainties, because harvest and inventory data are available only at national scale without error estimates.

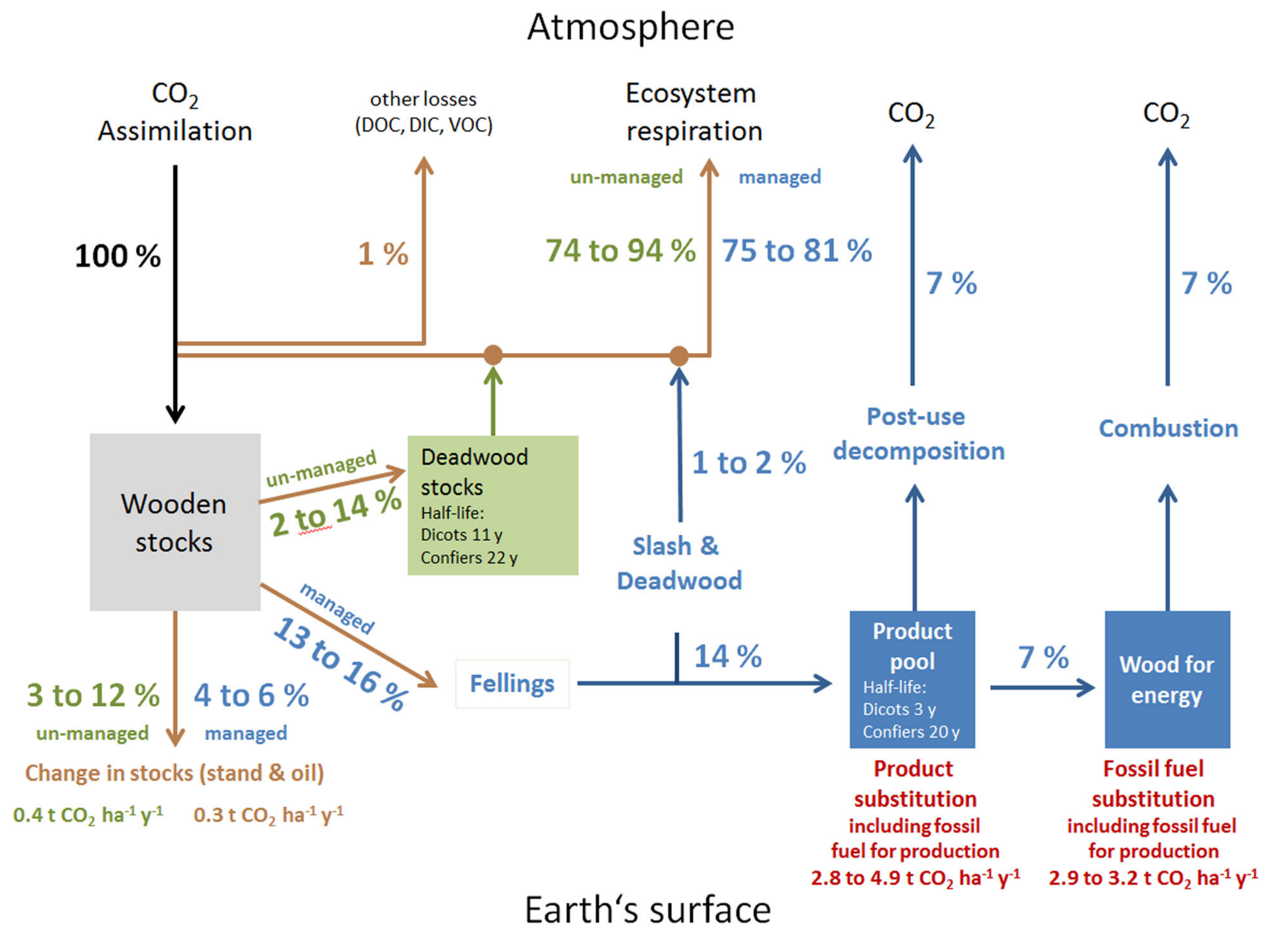

Fig. 1 Schematic drawing of a forest enterprise that is subdivided into 10 compartments and each of the compartments consist of 3 sub-compartments. Following a 10-year management plan, each sub-compartment is affected once in 10 years, exporting the equivalent of wood that is accumulating on the remaining untouched area as harvest. Here, we show only 3 out of 10 years. In the center of the property, an eddy flux tower exists which may never "see" the management action, except at night, where the footprint is lager. The owner may avoid harvest on the tower-plot in order not to disturb the flux measurements

In forests, the turnover of leaf and root litter contributes to the main fraction of the carbon turnover (Clemmensen et al., 2013, Sierra et al., 2021). Only about 2 to 14% of the carbon cycle is via dead wood under protected conditions and 4 to 6% under management. Under management conditions, about 13 to 16% of the carbon cycle is harvested and channeled into products, and only about 7% of GPP are eventually used for energy. Thus, harvest is a lateral carbon flux in which decomposition or release of carbon takes place outside the ecosystem where the carbon was fixed. Consequently, we expect that ecosystem respiration at landscape level should be reduced under management as compared to protected conditions, irrespective of changes in the stand microclimate due to harvest (Schulze et al., 2019).

In the following, we like to discuss the main fluxes based on existing data from observations on experimental plots (Table 1). Some of the flux stations operate with continuous measurements at a fixed location since more than 30 years (Aubinet et al., 2000). Surprisingly, Table 1 indicates that differences between managed and protected stands were not significant in most cases. Nevertheless, we would like to highlight some general trends.

2.1 Ecosystem carbon uptake by photosynthesis and losses by respiration

The input to the protected and managed systems is photosynthesis, termed as gross primary production (GPP) in flux studies. There are very few data available that explicitly study the effect of management as opposed to protection. To our knowledge, Herbst et al. (2015) is the only study to make this comparison, where a tendency of 3% higher GPP under management was observed in a beech forest. This was confirmed by the global database of Luyssaert, but not by Bond-Lamberty (Noormets et al., 2015). In these datasets, managed and un-managed plots were compared irrespective of their position to each other. We think that positive feedbacks of harvest should exist on GPP whereby the partial canopy opening in managed forests results in more light and water and nutrients for the remaining trees which would increase GPP per leaf area. The effects on groundwater depend on species and associated changes in leaf area and canopy structure (Schulze et al., 2019). However, the significance of the effect of management on GPP remains to be demonstrated. Inventory studies suggest that growth is higher under managed than under conditions of conservation (Table 2), but this could also be an effect of allocation (Schulze et al., 2019).

Ecosystem respiration was estimated as an average of coniferous and broadleaved managed forests for Europe in Schulze et al. (2009). A separation between conifers and broadleaved species reflects the differences in leaf area, foliage turnover, and canopy structure. Herbst et al. (2015) observed a 2% decrease and the Luyssaert database a 3% decrease with management. This contrasts to a 22% increase of respiration with management based on the Bond-Lamberty database (Noormets et al., 2015). If carbon is exported and released into the atmosphere elsewhere, as it is the case with harvest, ecosystem respiration should subsequently decrease. However, such decrease was also not observed in various thinning experiments (Granier et al., 2000; Vesala et al., 2005; Saunders et al., 2012), which rather reported an increase possibly related to the increase of dead biomass (slash and root stocks) from harvest and the partial opening of the canopy. A decrease in respiration was observed by Lindroth et al. (2018) that was explained by higher removal of biomass. Likewise, changes to the microclimate could have opposite effects, with less precipitation interception by the canopy cover resulting in more soil moisture, but also increased incoming radiations resulting in a faster drying of the upper soil, which has strong negative feedback on the respiration. As suggested by Moore et al. (2013), the reduced input (such as litter fall) is probably the dominant factor in the harvest-respiration relation. Thus, the influence of wood harvesting on soil respiration remains controversial (Moore et al., 2013, Mayer et al., 2017).

Ecosystem respiration (Reco) would be covered by heterotrophic soil respiration (Rhsoil) and by respiration of living biomass. In the database of Luyssaert and Bond-Lamberty (Noormets et al., 2015), the sum of plant and heterotrophic soil respiration exceeds total ecosystem respiration and GPP. According to Ciais et al. (2020), soil respiration remains as one of the largest and most uncertain flux. It remains inherently difficult to estimate soil fluxes, partly because soil CO_2 emissions tend to be clustered both in time and in space, in unpredictable so-called hot spots and hot moments (Leon et al., 2014) making their survey particularly challenging (Phillips et al., 2017). Modeling the long-term fluxes and the sequestration rate of carbon in soils, Sierra et al. (2021) showed that most of the leaf and root litter is being decomposed within few years, and only little of the carbon remains in the ecosystem over longer time spans. Nevertheless, total ecosystem-respiration is lower than GPP by about 200 to 500 gC m^{-2} $year^{-1}$ that could feed changes in stand volume and to a small extent in soil organic matter (changes in storage) and lateral transport of carbon by harvest and other losses even though ecosystem respiration was not reduced.

2.2 Effects of harvest on ecosystem respiration

A decrease of respiration equivalent to the amount of wood removal has not been observed in any of the plot studies. The mismatch between a theoretical effect of harvest on ecosystem respiration and field observations may be explained by three hypotheses: (1) there is a strong feedback between harvest and the remaining stand in such a way that the remaining trees operate more efficiently after receiving more light, water, and nutrients, (2) there is a geographic mismatch between stationary observations on experimental plots as compared to a dynamic use of land by harvest, i.e., harvest may occur outside the footprint of the tower, or (3) the amount of export of living and respiring biomass is too small to be detected by flux measurements, considering the large variation of fluxes with climate and other disturbances. The ability of eddy covariance systems to measure soil fluxes under low turbulence remains largely debated (Phillips et al., 2017, Barba et al., 2018), but the current consensus is that its overall resolution is not sufficient to quantify the magnitude of soil respiration fluxes (Speckman et al., 2015). The export of harvested wood contains mainly heartwood that does not respire.

The mismatch between stationary plots and landscape-scale operations is illustrated in Fig. 2 showing the outline of a model property that is divided into 10 compartments of different stand age, based on a 10-year management plan. Each compartment is subdivided into 3 sub-units, because it may take 30 years (equal to 3 management plans) to achieve natural regeneration. In each year, only one tenth of the land area is affected by tending, thinning, and harvest. In the center of the property, an eddy tower exists which has a much smaller footprint than the size of the property (50 to 200 m at daytime, and 500 to 2000 m at night). Thus, management activities on the property may never be "seen" by the eddy flux tower, even though the amount of exported wood includes the sub-compartment of the tower. The variation of data in Table 1 may result from this geographic problem.

An alternative explanation of the observations may be that harvested wood consists mainly of dead biomass in heartwood of standing trees that accumulated for

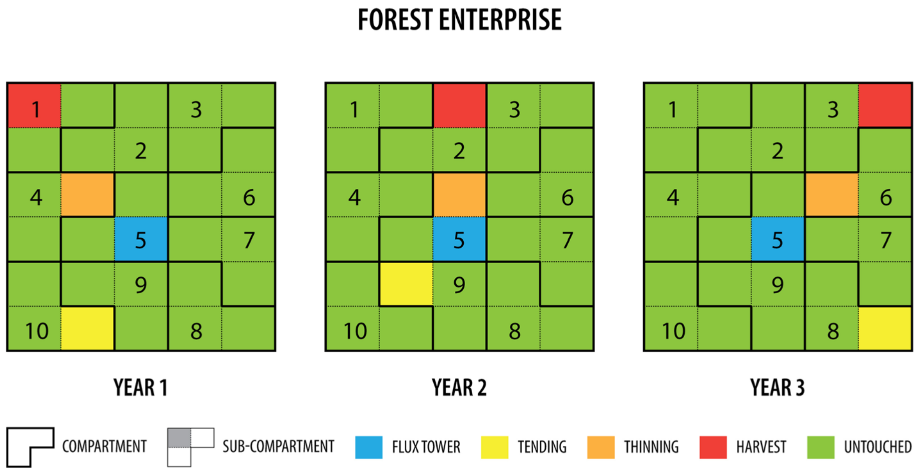

Fig. 2 The carbon cycle of managed and protected temperate forests and of harvest and wood use in Germany. Data from Table 1, Schulze et al. (2020), and from Grossmann (2020). DOC, dissolved organic carbon; DIC, dissolved inorganic carbon; VOC, volatile organic carbon. There is an effect of tree species on the way wood is being used in products. Here, we separate between conifers and broadleaved species. The rate of sequestration and substitution are based on national inventories (Schulze et al., 2020). Green: unmanaged forest, blue: managed forest, brown: common fluxes

decades. As a tree grows, only part of the stem remains as sapwood which conducts water and nutrients and which has living parenchyma cells that respire. The center of the stem dies of and this part does not conduct water nor does it respire. Nevertheless, heartwood remains as an essential structural element of a tree. Being dead, it has no effect on instantaneous autotrophic (Ra) and heterotrophic (Rh) respiration, and the harvested biomass is balanced by growth of sapwood of other stands at the landscape level, which would be

Table 1 Comparison of ecosystem flux data and ecosystem lateral fluxes. [gC m^{-2} $year^{-1}$]. Percent values indicate managed as percent of protected from the same data source

Parameter	Source	unmanaged	managed
Gross Primary Production, GPP	Schulze et al. 2009	1107	1107
	Herbst et al. 2015; Knohl personal commun ication	1575	1627
	Noormets et al., 2015: Luyssaert database	1562	1698
	Noormets et al., 2015: Bond-Lamberty database	1989	1887
Ecosystem respiration, Reco	Schulze et al. 2009	857	857
	Herbst et al. 2015; Knohl personal commun ication	1063	1042
	Noormets et al., 2015: Luyssaert database	1460	1460
	Noormets et al., 2015: Bond-Lamberty database	1698	1384
GPP-Reco	Schulze et al. 2009	250	250
	Herbst et al. 2015; Knohl personal commun ication	512	585
	Noormets et al., 2015: Luyssaert database	102	238
	Noormets et al., 2015: Bond-Lamberty database	291	503
ecosystem turnover and plant respiration	leaf and root turnover (Bond Lamberty database)	377	491
	plant respiration (Luyssaert database)	1133	1460
	soil respiration (Luyssaet database)	923	1013
	sum	2056	2473
ecosystem storage and export	Change in stand volume (Schulze et al. 2020; Schulze et al. 2020a,b)	0,4 - 225	35
	Change in soil Carbon (Wellbrock et al. 2019)	40	40
	harvest (Schulze et al. 2020)	0	230
	sum	40,4 - 265	305

visible only as Ra. Heterotrophic respiration (Rh) could be affected by heartwood when the whole tree dies and the stem becomes "deadwood." However, heterotrophic respiration from dead wood is only a small component of Rh which is mainly driven by the turnover of leaves and roots (Hanson et al., 2000, Clemmensen et al., 2013, Ekblad et al., 2013, Brunner et al., 2013). Thus, Rh is not affected by the removal of wood that consists mainly of non-respiring heartwood, unless it rots (Oren et al., 1988).

In view of C-fluxes, the process of heartwood formation should be regarded as an additional lateral flow of carbon into a non-respiring compartment until wood rots in situ or is used for energy. In the case of management, the carbon locked in heartwood would be unlocked either by decomposition or by combustion at a different location under conditions of wood-use. This emission must be associated with the ecosystem flux balance at least at the national scale. There is a time-lag between sap-wood formation (wood production), heart-wood formation, and decomposition under conditions of sustainable management, and the age structure of the forest at landscape scale replaces time by space, which means that the harvest is photosynthetically regenerated at the latest at the time scale of a management plan (10 years). In terms of flux observations, the amount of wood that is extracted by harvest and that needs to be considered in the mass balance approach of the carbon cycle is too small to be detected in a flux balance considering the variation of other factors. The mismatch between plot-scale and landscape scale observations could be a consequence of different scales in time and space (see Cowie et al., 2021).

2.3 Ecosystem storage

If ecosystem respiration is smaller than GPP, a change in ecosystem carbon contents is to be expected which would take place as change in living and dead biomass including soil carbon, where changes in the living biomass are large compared to changes in soils (Schulze et al., 2019) The quantification of the volume change of aboveground biomass under protected and managed conditions is of special interest. Ecosystem "storage" would be the resultant total amount of living and dead biomass. The number is important because it quantifies the amount of carbon that can be accounted for by the forest sector according to the IPCC Guidelines (IPCC Guidelines, 2006). In the case of harvest a certain part of this amount would actively reduce fossil fuel fluxes by substitution of products that require large amounts of energy in the production process (e.g., steel and cement; product substitution) or replace fossil fuel in the process of energy generation (Knauf et al., 2016). For managed forests the change in storage is quantified as net volume change by national forest inventories and by private inventories for a 10-year management plan. However, for protected forests, this number remains largely unknown (see Irslinger, 2021). There are numerous plot studies that indicate high changes of stand volumes in single protected forests, but these observations do not comprise disturbance-related voids and there are no assessments at landscape or management-unit scale of the mean achievable stocks (Körner, 2020). High storage refers generally to stands that were put under protection few decades ago.

Luyssaert et al. (2008) already pointed out that particularly old forests are comparatively rare even in completely untouched forest wilderness landscapes due to the cumulative probability of disturbances. Old forests can only develop if large-scale disturbances are absent for centuries, which may be regarded as an unusual situation. Old-growth forests are not immune to disturbances: they can disappear and eventually redevelop (Jandl et al., 2019). In Korpel (1995) "stages of decay" occur in the primary beech forest on 42 to 45% of the primary forest area, while the "optimal phase" with maximum wood stocks occurs on 20 to 22% of the area. The surveys by Korpel (1995) involve the natural disturbance regime of the landscapes examined. The percentage of the areas of the individual development stages does not change over time under constant climatic conditions, but the location is dynamic at landscape scale.

In order to be able to assess the carbon stocks or the sink function of forests under the conditions of a natural succession, all stages of the forest cycle must be taken into account on a landscape scale and not only those that are rich in biomass or those that are currently strongly accumulating (Ehbrecht et al., 2021). Also, it remains unclear of what is protected without wood removal and since when (Wirth et al., 2009). The broad range of ecosystem storage of protected forest results from differences in spatial scale. In Table 1, the large number (225 gC m^{-2} $year^{-1}$) originates from plot studies, while the small number (0.4 gC m^{-2} $year^{-1}$) originates from a volume change at landscape scale, including disturbances, regeneration, and area extensions of entire properties. Irrespective of management, the landscape consists not only of one age class of forest, and changes in forest area are part of the dynamic at landscape level. Theoretically, it is quite clear that freezing wood procurement should lead eventually to an equilibrium where forests reach a balance between absorption of CO_2 by photosynthesis and release of CO_2 by ecosystem-respiration and where no further increase in stocks is possible (Gundersen et al. 2021, Paul et al. 2021, Stillhard et al., 2021) and where increasing stocks is a risk of stand collapse (Loisel, 2020, Forzieri et al., 2021). Furthermore, the continuous accumulation of biomass is stimulated by the input of nitrogen from atmospheric deposition (Gundersen et al., 2021).

In order to be able to assess proforestation strategies (Moomaw et al., 2019) with regard to climate protection, it is necessary to compare the current wood stocks of sustainably managed forests with protected forests at a landscape level. Soil carbon must be included in this comparison, whereby sustainable forest management has no negative impact on the organic carbon of the soils at a landscape level (Achat et al., 2015, Johnson and Curtis, 2001, Nave et al., 2010). Sustainable forest management also includes the conservation of soil stocks of nutrients, especially basic cations (FVA Baden-Württemberg, 2018).

When harvested trees are processed into wood products, e.g., wooden houses, an additional storage of carbon outside the forest is created (Rüter, 2011). If a managed forest landscape is in an equilibrium state with high timber stocks, more carbon can be stored in the forest and product pool together than in the case of a proforestation strategy. The carbon in the product pool, like the carbon in the forest, is part of the natural C cycle and delays the emission of carbon. This is important to avoid tipping points of the climate.

There are few studies to show growth, respiration, and net emissions as related to standing aboveground biomass. By using repeated inventories, Paul et al. (2021) showed for the Southern Beech in New Zealand that net volume change increases initially in a growing stand, but levels of when the stands reach about 400 m^3/ha, while ecosystem respiration continues to increase exponentially. Thus, forest stands become a net CO_2 source at a stand volume of about 400 m^3 ha^{-1}. This observation seems to hold also for European broadleaved forests where the protected old stands of the Ukraine (Stillhard et al., 2021) do not show a net accumulation of stand-volumes, nor of basal areas. The compensation point at which stands become a net source will depend on the main canopy species.

2.4 Storage capacity of forest ecosystems

Table 2 shows that average and maximum biomass of sustainably managed forests in Central Europe at the time of harvest and regeneration is as high as it would be without management (Korpel, 1995, Schulze et al., 2019, Bouriaud et al., 2019) based on *Fagus*- and *Picea*-dominated forests. Following Luyssaert et al. (2008), NPP and NEP have a minimum in very young and very old stands and reach a maximum between 30 and 100 years. In managed forests, a stage of high biomass persists for about two to three decades until regeneration has established. We expect that, as a result of climate change, the ability of landscapes to store carbon will decrease due to an increase in forest types with lower carbon storage potential. Highly stocked forest ecosystems will increasingly become an unknown source of greenhouse gasses in the future with increasing the stocking and forest age. The higher the stocks and the older the forests, the greater the potential emissions of CO_2 (Allen et al., 2015, Hurteau et al., 2008, Millar and Stephenson, 2015, Schmidt et al., 2010, Seidl et al., 2014, Seidl et al. 2017, Thom and Seidl 2016). Consequently, the carbon stocks in protected forest ecosystems are unstable as can be seen from the effects of a dry year in 2018 (Thüringen Forst 2020). The expected increase of large-scale fire-, wind-, or insect-related disturbances indeed suggests that stocks are likely to decrease on landscape level making the reach of maximum stocking capacity less probable (Seidl et al., 2014, 2017, Mantero et al., 2020). It would be a risky policy as recently exemplified by the World Heritage UNESCO forests where over 10 sites became net carbon sources (UNESCO 2021). Depending on the severity of the disturbance, the regeneration ability may be low (Kuuluvainen et al., 2017) with long-lasting depreciative effect on the biomass stocks. Therefore a "proforestation" strategy (Moomaw et al., 2019) which intends to increase forest biomass cannot be justified for sustainable forest management in terms of climate mitigation. "Storage" of carbon in forest biomass is of great risk under climate change conditions, and the owner may have to pay back any subsidies that were donated for storage. Accumulating carbon stocks in forest ecosystems beyond a certain level accepts that large amounts of CO_2 could be

Table 2 Average and maximum biomass, stand age, and increment of managed and unmanaged broadleaved and coniferous forest (Schulze et al. 2020)

	Broadleved (Fagus)			**coniferous (Picea)**		
	un-managed	**managed**	**significance**	**un-managed**	**managed**	**significance**
average stocks (m^3 $ha-^1$ life&dead wood)	435+34, *n* = 332	366+6, *n* = 9104	***	421+37, *n* = 308	425+6, *n* = 15073	n.s.
Maximum stocks (m3 ha-1 live&dead wood, >94.Perzcentile	981+148, *n* = 46 of 732	919+195, *n* = 776 of 15519	n.s.	1118+202, *n* = 43 of 859	1098+201, *n* = 1456 of 29113	n.s.
area weighted age (yrs)	115	101		94	69	
increment (m^3 $ha-^1$ $yr-^1$)	8.99+0.9, *n* = 327	10.28+0.16, *n* = 8746	***	9.01+1.04, *n* = 271	13.95+0.16, *n* = 14219	***

emitted in the next few decades due to global warming. Curiously, carbon debts and payback time are not discussed under these “high capitalization” strategies, though the relation between high stocks and high debt is immediate. Conversely, increasing or securing the existing stocks requires active measures oriented towards higher stability and resilience (Dobor et al., 2020, Zimová et al., 2020).

In addition, forests diminish their net carbon uptake when aging (Luyssaert et al., 2008; Paul et al., 2021). Even if old growth forests may remain a carbon sink under the absence of disturbances, their net sink capacity is small compared to that of young stands. Thus, the strategy of aging the forests leads to a reduction of the forests carbon uptake in relatively short term. Carbon uptake is currently quite large in Europe (Ciais et al., 2020) due to an uneven age structure which is based towards younger age classes (Forest Europe, 2016). Also, forest increments are currently largely used for wood supply (BMEL, 2015), and they are exposed to considerable nitrogen depositions from the atmosphere at increasing levels of CO_2 concentration (Schulze et al., 2019). The use of wood therefore has the direct consequence that forests are maintained in a state of high net productivity with active atmospheric CO_2 absorption and sequestration, at rates undoubtedly higher than that of old-growth forests.

3 Use of wood and substitution effects of fossil-fuel emissions

Irrespective of the uncertainties of estimating storage from ecosystem fluxes, it emerges that all the carbon that enters into the harvest pathway returns to the atmosphere. Thus, wood-use is a bypath of natural decomposition. In this context, the half-lives (e.g., the time for 50% decay of the original dry weight) of carbon in the harvest and non-harvest pathway become important. Schulze et al. (2021) showed that the half-lives of products are similar to the half-live of wood during decomposition.

3.1 Effects on substitution

Carbon in products and product turnover are part of the biosphere-atmosphere carbon cycle where the return-times are independent of the fact that wood contains less energy than fossil fuels, and independent of carbon storage in the ecosystem. Thus, the use of wood for products (product substitution) and burning of wood for energy production (energy substitution) is carbon neutral under sustainable management confirming the findings of Taeroe et al. (2017) and Sjølie and Solberg (2011) as long as conditions of sustainability are met. In addition, the on-site increase in wood volume (storage) does not contribute to a reduction in fossil fuel use (Fig. 3). Fossil fuel is being avoided only by product and energy substitution (Nabuurs et al., 2017). Schulze et al. (2020) showed for Germany at national scale that the energetic use of the harvested woody biomass from sustainably managed forests results in a net saving of 2.9–3.2 t $CO_{2\text{-equiv.}}$ ha^{-1} $year^{-1}$ when accounting also for the efficiency of energy conversion. This amount does not yet include the energy saving by production of wood-products instead of products made from iron, aluminum, glass, or concrete. Product substitution was estimated to be 2.8–4.9 t $CO_{2\text{-equiv.}}$ ha^{-1} $year^{-1}$ and thus be even higher than the energy substitution (2.9 to 3.2 t $CO_{2\text{-equiv.}}$ ha^{-1} $year^{-1}$; Knauf et al., 2016, Schulze et al., 2020). Following Roux et al. (2020), this is about 10 to 14% of the German emission balance (Schulze et al., 2021).

The substitution effect varies with nations as it would depend on the way energy is produced. In Germany for instance, the substitution effect is larger than in other countries of Europe, e.g., France where a large fraction of its electric energy is produced by nuclear power-plants. At the same time, Germany reaches a higher level of harvest on a smaller land area than France, due to a higher fraction of conifers, and due to more favorable climate.

In the case of sustainable managed forests, the authors cannot recognize any “carbon debt” because the carbon contained in harvested wood is re-assimilated by the re-growing biomass at landscape scale as it is released by product use (see Cowie et al., 2021). The time to sequestration parity of wood depends on what energy it replaces (Repo et al., 2012), but it also largely depends on the productivity, and was found to be quite reduced for intensive forest managements (Ter-Mikaelian et al., 2014). The main indicator for sustainability at landscape scale is that carbon stocks remain constant, which distinguishes sustainable forestry from exploitations where harvest exceeds growth. Conditions for the carbon neutrality of using wood for energy production hence include the fact that harvest does not exceed the amount of biomass that would have decayed naturally otherwise (Ter-Mikaelian et al., 2015). This assumes de facto a steady-state of landscape-level biomass. In Europe, however, the stocks have increased during the last decades, despite intensive use of forests (Ciais et al., 2008). Contrary to the wood stored in the ecosystem that only “compensates” atmospheric fossil CO_2 increase without affecting emissions, the harvested wood contributes to a reduced use of fossil fuel. In addition, avoidance of fossil fuel use by product and energy substitution is permanent, while storage of carbon in the ecosystem is temporary due to the lability and associated risks of the forest carbon stocks (Raymer, 2006, Forzieri et al., 2021).

3.2 The use of wood for bioenergy

The low energy density of the wood is of concern to environmentalists (Spiegel, 2020) when using wood for

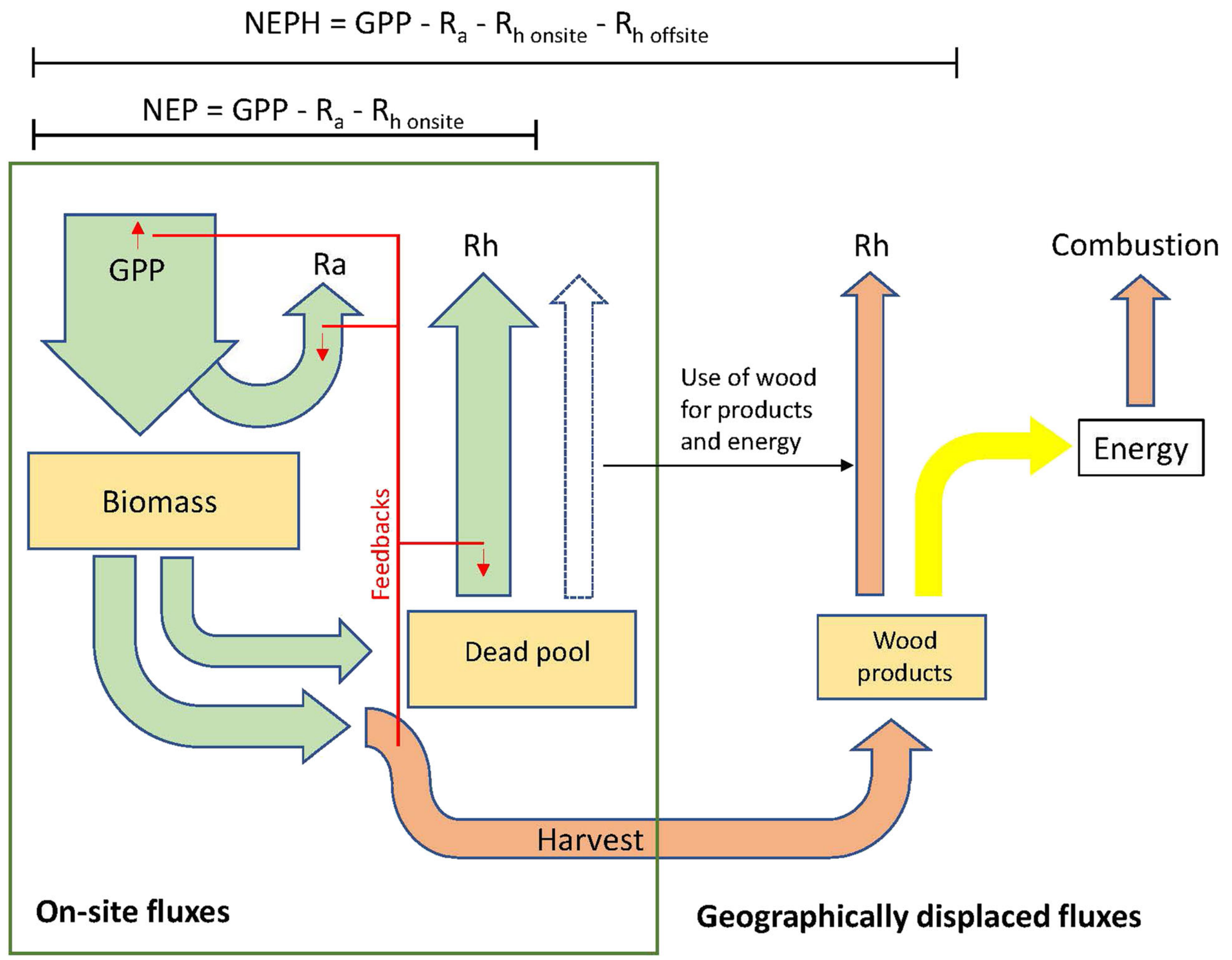

Fig. 3 Schematic presentation of the effects of non-management and of management on atmospheric CO_2

energy. Table 3 shows that the energy content of unprocessed wood is lower than that of most fossil fuels, but higher than the energy content of agricultural residues. Corn-based ethanol has less energy per liter than it takes to produce it (Pimentel et al., 2009). Wood products are in a much better position. This difference almost disappears when inspecting the CO_2 emissions of various energy sources. Emissions of liquid fossil fuels are lower and of agricultural residues are higher than those of wood. When fossil fuels are burned, carbon from the earth's crust enters the biosphere-atmospheric cycle, whereas the carbon in the wood is already part of it. Since it is the political objective to reduce net emissions by mainly reducing fossil fuel emissions, the comparison with fossil fuels is not appropriate and the use of wood remains more effective than the use of agricultural residues. In fact, small forest land holders in rural areas use their forest mainly to generate fire wood, and thus do not use any fossil energy for heating. These land-owners fulfill the envisaged reduction of fossil fuel use even today.

Table 3 Comparison of various energy sources with respect to their energy content and their CO_2 emissions (FNR 2018)

Energy source	Energy content (kWh/kg)	CO2-emission (kg CO2/kWh)
Narural gas	12,5	0,20
Diesel	11,8	0,27
Hard coal	7,4	0,34
Lignite	5,3	0,35
Wood	5,2	0,35
Straw, Hay	3,9	0,47

Bioenergy wood is a byproduct when harvesting construction wood. A harvested stem always contains a fraction that only can be used for energy. In addition, processing of wood generates byproducts (sawdust, shavings) that are presently used for energy. It could be that these byproducts will be used in a cascade use for other products in the future, but also these will be used eventually for energy. For these reasons, the use of domestic forests and a regional fuelwood market remain as a basic module of climate protection. In Germany, about 8% of the total energy production originates from biomass (FNR, 2018). Due to its low energy content, transporting firewood (e.g., in form of pellets) over very long distances is not an efficient option (FNR, 2018). Furthermore, freezing the procurement of wood in Europe will inevitably lead to increase the import of wood and pellets from a longer distance (e.g., from Siberia and Canada) with detrimental effects on the emissions and on the low-productivity stands of these regions (Schulze et al., 2016) or it will require an increased use of fossil fuel. The use of wood from forests outside Europe is usually not CO_2 neutral (see Köhl et al., 2020). Agave and other species are presently tested for production of particle boards in Mexico (Moreno-Anguiano et al., 2021) in face of the conservation strategies of the EU (EU, 2020). Furthermore, increasing the pressure of wood use on forests with high diversity but far smaller protection measures would have direct and irreversible detrimental effects on global-scale biodiversity.

The problem of accounting emerges from the IPCC Guidelines where the forest sector is separated from the energy sector. Thus, in the national IPCC reports, forestry can only account for wood that is stored as biomass in the forests and in products made of wood. It is the energy sector that records a decrease in fossil fuel consumption. However, since bioenergy comes not only from forestry source, a simplified accounting scheme had been established with the Kyoto protocol: Any wood harvest is accounted as immediate emission in the forest sector independent of the life-time of products. Emissions from bioenergy remain unaccounted in the energy sector. To estimate the contribution of forestry to climate mitigation, the amount of fossil fuel saved by products and biofuels should not to be accounted as an immediate emission, but as an achievement of the forest sector. A proper consideration of the contribution of forests through products and bioenergy would consequently change the estimated costs of meeting EU greenhouse gas targets (i.e., reducing greenhouse gas emissions by 80–95% by 2050) which are currently obviously tilted towards sequestration (Vass and Elofsson, 2016).

The accounting of harvest as emission inhibits the possibility to including harvest in certification schemes of balancing fossil fuel emissions. In this context, harvest is not a loss of carbon but a positive contribution for substitution. The loss of carbon from the biosphere occurs only with decomposition and with burning of biomass. The lack of recognition of on-site forest harvested products as a positive mitigation contribution to climate policy undermines the willingness of private owners and public bodies to take care of forests and the landscape.

The sustainability definition of the EU includes not only forest structure, but also social and economic parameters (Resende et al., 2021). It is beyond the scope of this study to discuss the environmental and social benefits of forests within the concept of sustainability.

4 Conclusions

Building up the carbon flow still remains a challenge today and the analysis of the data available point to a discrepancy of the estimation of the major fluxes and their response to harvest. By harvesting trees, the carbon balance of forest ecosystems seems unchanged; thus, the energy represented by the emissions from harvested wood is bypassing the forest area. If not burnt, the carbon in wood would reach the atmosphere via decomposition without substituting fossil fuels. Therefore, using wood from sustainably managed forests is carbon neutral. The half-lives of products are similar to the half-live of wood during decomposition. Under sustainable management no “carbon debt” is recognizable at landscape scale.

Here, we suggest that on-site changes in forest carbon stocks on a landscape level represent a risky and improbable target. They should be zero under sustainable management and in an equilibrium state of natural forest development. When harvested trees are processed into wood products, an additional stock of carbon outside the forest is created. Stopping wood supply from domestic forests could have detrimental effects to global climate mitigation.

The main contribution to mitigation of sustainable forest management is not an “immediate emission” but a replacement of fossil fuels by regenerative materials. It is the avoidance of fossil fuel use for energy production. This is independent of the energy density of wood.

The process of harvesting wood should become certified as a climate mitigation strategy.

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Code availability

Not applicable.

Authors’ contributions

Concept and original draft: Schulze, methodology: Bouriaud, product substitution: Irslinger, Eddy covariance: Valentini. The authors read and approved the final manuscript.

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Availability of data and materials

The datasets generated in this study are available from the corresponding author on request.

Declarations

Ethics approval and consent to participate

The authors declare that they follow the rules of good scientific practice. The authors declare that the study was not conducted on endangered, vulnerable, or threatened species.

Consent for publication

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

Competing interests

The authors declare that they have no competing interests.

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