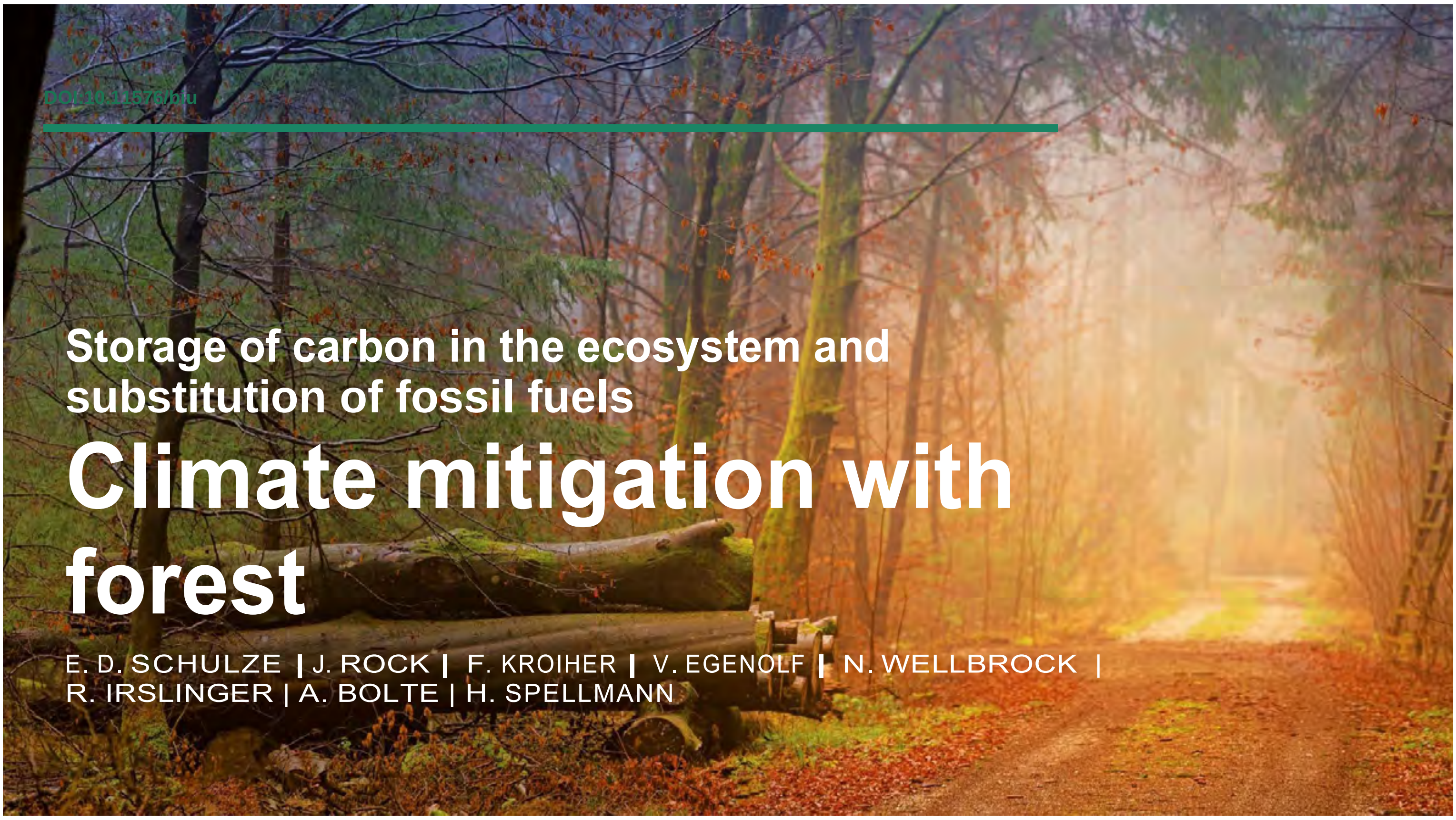

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Storage of carbon in the ecosystem and substitution of fossil fuels

Climate mitigation with forest

E. D. SCHULZE | J. ROCK | F. KROIHER | V. EGENOLF | N. WELLBROCK | R. IRSLINGER | A. BOLTE | H. SPELLMANN

The "Fridays for future" movement has greatly stimulated the public debate on climate protection. The overriding goal of effective climate protection is to reduce the consumption of fossil fuels [1]. The planned closure of Germany's lignite mines is a clear sign of this. In addition, land use forms must also exploit all potentials for savings in order to achieve the ambitious political goals while the total energy demand continues to grow. The use of forests is a controversial issue in this context because very different interests collide here. It is not only about climate protection, but also about biodiversity, the public utility of properties, the rights of owners as well as the sustainability of use. In the following, different options for the contribution of forests to climate protection will be presented.

The path of wood from the forest through the processing chain into wood products up to the microbial process of decomposition or its energetic use leads through many stations (Figure 1). In addition to the provision of wood, the commercial forest fulfills other ecosystem services, in particular the regulation of material cycles, the provision of drinking water, biodiversity and recreation. Clarifying its function in climate change mitigation is the goal of this work. Alternatively, the forest area could also be used for technical energy production.

Forest management usually aims at the implementation of different human demands on the same area. These demands range from the provision of wood, the supply of clean water and recreational use. Despite a comprehensive analysis of climate mitigation in agriculture and forestry [2], the public and the forestry sector are currently discussing five different options for how forests can contribute more effectively to climate protection (Figure 2):

Option 1: No wood is used in the forest to allow it to grow and die on its own. Dead biomass decays in the forest and releases photosynthetically bound carbon via microbial respiration.

Option 2: Wood is harvested and delivered to wood users and energy producers. Until the trees are ready for harvesting, a large part of the increment remains in the forest, even when wood is used, and leads to a build-up of the carbon stocks stored in the biomass.

Option 3: The harvested wood is stored in products and replaces competing materials that are produced with high energy requirements (material product substitution).

Option 4: The wood is used for energy directly or after prior use in wood products and replaces the consumption of fossil fuels (energy substitution).

Option 5: Forest area is used for energy production with wind turbines or solar panels. This would be a change in land use or a restriction of forest management.

Even though this article deals mainly about the amount of wood, the possible uses depend on the diversity of the woody plants.

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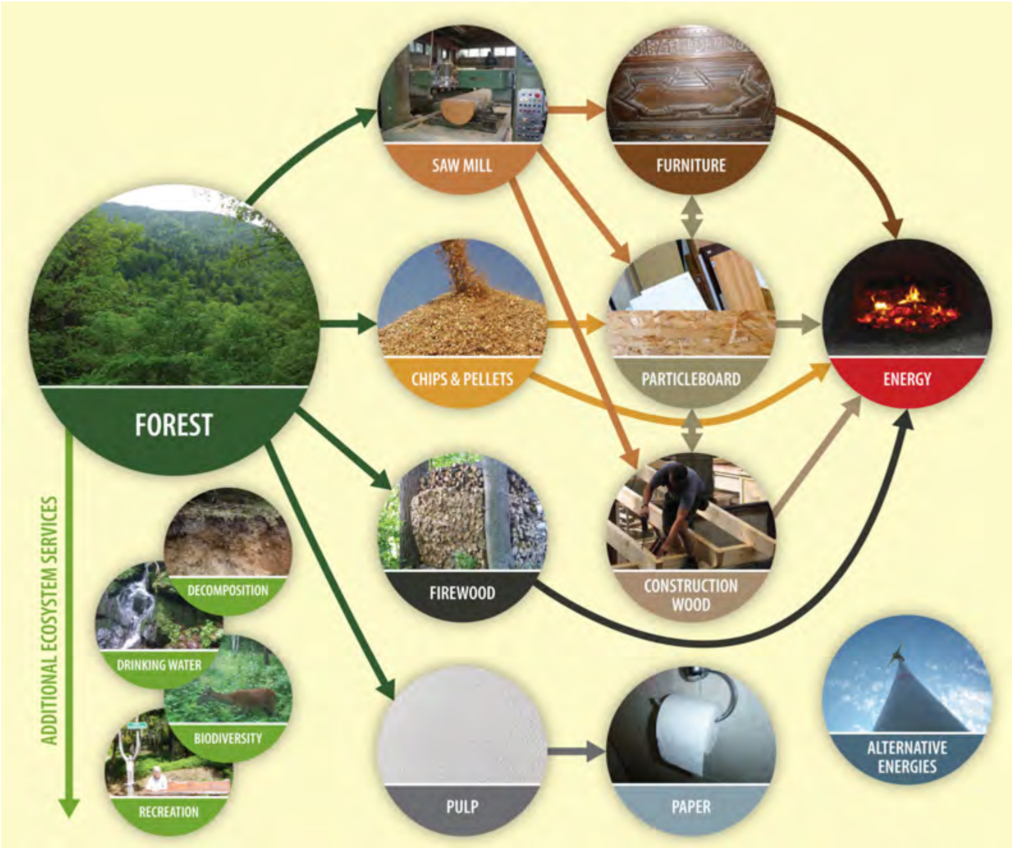
The use of tree species diversity, however, is subject to major changes in terms of quantity and type. In Soravia's book on forest utilization (1877) [3], 63 species of wood are described: 52 species were used medicinally, 40 species were used to make objects, 32 species were needed to make paints, and firewood was obtained from 32 woods. A little more than a century later, little has remained of this diversity of use [4]. By the end of the 20th century, many of the uses were replaced by metal, plastic and chemical products. Twenty woody species have become ornamental plants and six of the formerly used species are now on the "red list", again 25 woody species are only used for landscape protection. Today, over 70 percent of the managed forest consists of only four tree species (spruce, pine, beech and oak). The example shows that in the past, the forest was used more intensively and in a more diverse way and was not protected. Historical forms of use such as grazing forests or coppice forests with a high diversity of tree species are hardly practiced anymore. Other forest types have been relegated to special sites. On the one hand, this is regrettable; on the other hand, this change in the use of tree species has no effect on the climate effectiveness of the forest. With decreasing number of used tree species, however, the risk of climate-related damage increases.

The recording of the forest's services for climate protection follows the IPCC guidelines [5]. The flow of carbon from living and dead biomass from the forest via wood products and energy use back into the atmosphere can only be described schematically (Figure 3). The inconsistencies of the actual carbon fluxes and the transport of wood for use, and their accounting in the climate protection performance, become clear. Forest management belongs here to the sector "LULUCF" (Land Use, Land-Use Change, and Forestry). For IPCC, the carbon in the wood that is removed from the forest is considered to be directly "emitted". In order to avoid double counting of emissions, emissions from wood are not recounted in the "energy" sector when it is burned and are not attributed to the "energy" sector (see Box 1 "Greenhouse gas monitoring and accounting").

FIG. 1 | THE PATH OF WOOD DURING HUMAN USE

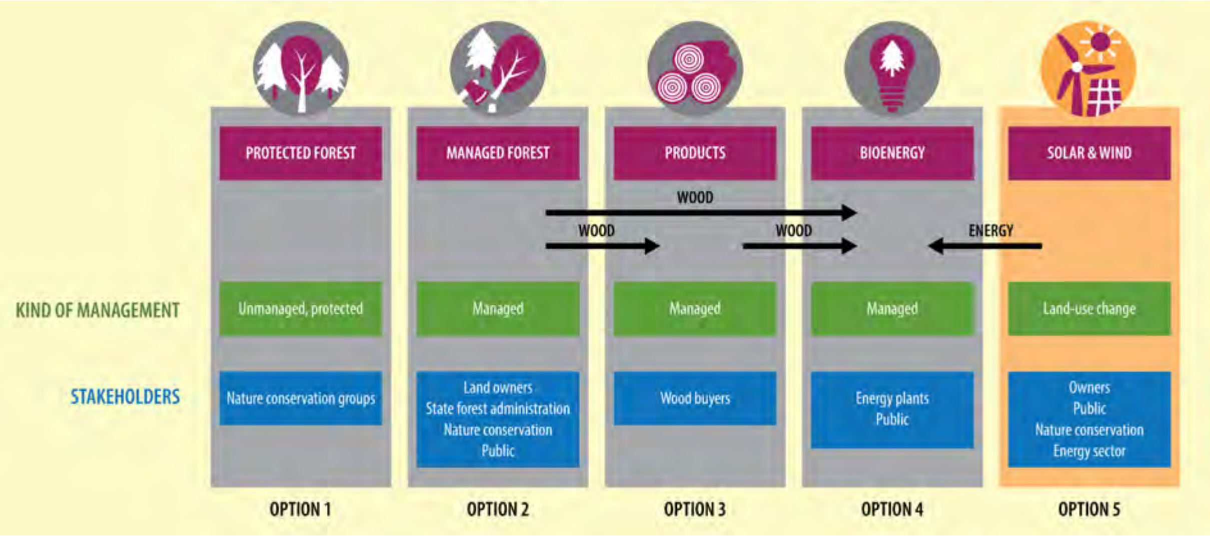


The path of wood from the forest through its processing into wood products to its microbial degradation or its use for energy passes through many stations. In addition to providing wood, the commercial forest fulfills other ecosystem services, in particular the regulation of material cycles, provision of drinking water, biodiversity and recreation. Alternatively, the forest area could also be used for technical energy production.

IN BREVITY

- *Sustainably managed forests in Germany contain the same amount of wood biomass per hectare of forest area as unmanaged forests at the time of harvest. Sustainable management takes* ***the natural development of a forest*** *for orientation.*
- *Wood products avoid the use of construction and other materials with high energy requirements in production ("product substitution") and* ***replace fossil fuels as energy sources*** *("energy substitution").*
- *The atmosphere is not additionally burdened by the energetic use of wood, because wood contains* ***recent carbon bound by photosynthesis****, which would alternatively be released by rotting.*
- *Forest management and wood use currently* ***improve Germany's greenhouse gas balance*** *by about 11% to 14%.*
- *The efficiency of land use for energy purposes in the forest could be increased by wind and solar plants. However, this would lead to* ***impairment of other forest ecosystem services*** *and is therefore controversial.*

FIG. 2 CLIMATE PROTECTION OPTIONS IN FORESTS AND THE INTEREST GROUPS TO BE CONSIDERED THEREOF



GREENHOUSE GAS MONITORING AND ACCOUNTING

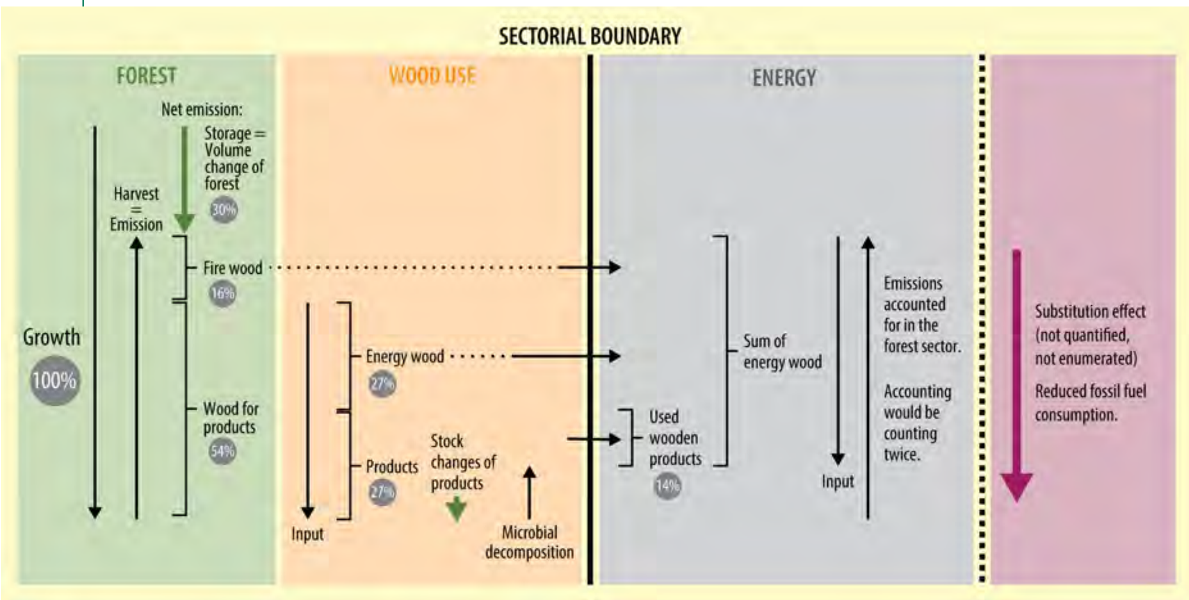
The Framework Convention on Climate Change (FCCC) requires that the monitoring of emissions and the removals of greenhouse gases (GHGs) occurs regardless of who is responsible for changes in the GHG balance. The Kyoto Protocol (KP) [20, 21] introduced legally binding emission reduction targets for signatory nations. However, the assumption of responsibility for the anthropogenic part of the carbon cycle follows partly different rules than the reporting under the FCCC, which is why values from the two systems cannot be compared. For example, reporting differentiated by seven sectors means that carbon in wood leaving the forest is considered emitted and therefore not accounted for as an "input" in energy production. This simplification is not significant for reporting [5, 6] by nations. However, for the assessment of cross-sectoral measures (such as forest management with wood use to energy production), the sectoral view is inappropriate, because emission optimization in one sector can lead to additional emissions in other sectors. Two aspects are important:
The KP expired at the end of 2020 and is de facto replaced by the Convention of Paris (CoP) and an EU regulation (LULUCF Regulation). The exact rules for accounting for GHG stock changes have not yet been defined, but will be based on the methodology of the IPCC-2006 Guidelines [5]. In the future, numbers on the forest complex will be available for Germany from four different systems (FCCC, KP, CoP, and LULUCF-regulations), which are not directly comparable due to the system differences.
There is an obligation to permanently improve the inventories, i.e. with better methods or new data sources, the values of previous years must also be recalculated. Therefore, only the most recent reports are valid [6].

The accounting of all emissions from harvested wood in the forest sector is a major point of criticism of the previous accounting rules, since the emissions are attributed to the forest and the reduction in the consumption of fossil fuels are accounted at other sectors of the economy. In addition, various interest groups would like to see their own priorities realized in forest management, often without having rights of disposal for their assets. The fragmentation of responsibilities and the efforts of different sectors to expand their influence in order to maximize the accounting of "their" contribution to climate protection make an overall assessment of the forestry and wood sector's climate protection performance difficult.

Storage of carbon in living and dead biomass in the forest (option 1 and 2)

In greenhouse gas (GHG) reporting, either the additions or the removals to various storage pools (in the forest: living and dead plant biomass, soils, wood products) or the change in the size of these stores over time are considered [6]. The woody biomass of tree stands in Germany was most recently assessed by the 2012 Federal Forest Inventory (BWI) and the Carbon inventory 2017 on a subnetwork of the BWI 2012 [7]. Both show stocks and changes in stocks in the tree stands and the correlating carbon quantities. According to the results of the second and third national forest inventories (2002 and 2012, respectively) in Germany, wood increment amounted to 1,252 million m^3 and the removals (utilization + mortality) to 1,091 million m^3, so that the timber stock increased from 3,436 million m^3 to 3,663 million m^3. Between 2012 and 2017, this wood stock increased again by 205 million m^3 and reached a record

FIG. 3 | CARBON FLOWS FROM THE FOREST OVER WOOD PRODUCTS AND ENERGY USE TO THE ATMOSPHERE



Since photosynthetic binding as a function of management is not reported, respiratory emissions are not reported either. Horizontal arrows show transport of wood from forest and timber management to energy production. Vertical black arrows show the "inputs" and actual emissions, the balances of which produce the thick green arrows (data adapted from [5]). These represent the currently reported storage changes in forest tree cover and in wood products. The length of the green arrow in product storage is over-scaled. The average carbon content is about 25 percent of the volume of fresh wood. The blue arrows represent calculated emissions from timber harvesting (utilization) and microbial degradation of wood products, respectively. Emissions from the provision and processing of wood are not included here.

high of 3,868 million m³ in 2017. Thus, 1,230 million tons of carbon was sequestered in living biomass in 2017. The annual rate of storage in living biomass was 1.1 tons C ha^{-1} $year^{-1}$ between 2012 and 2017 (see Box 2 "The growth of a forest"). Because the area share of the high-growth age classes of 21 to 60 years decreased by 7 percent, the increase in the period 2012 to 2017 decreased from 11.3 to 10.7 m^3 ha^{-1} $year^{-1}$ compared to the period 2002 to 2012. In living biomass and deadwood, however, a net additional 13.2 million tons of carbon were still accumulated in the forest per year [8].

"Sustainability" is the "magic word" coined by H. C. von Carlowitz in 1732 in his "Anweisung zur wilden Baumzucht": *"It will become a major art of science*

THE GROWTH OF A FOREST

The growth of a forest depends on the tree species, the structure and age of the stands, and the site conditions [22]. A tree forms a new growth ring every year, which expands the water- and nutrient-conducting living part of the wood (the sapwood). At the same time, the sapwood inside the trunk continuously dies and forms additional heartwood [23]. However, the amount of carbon removed from the atmosphere does not correspond to the increment of a single tree, but to the increment of all trees on an area composed of predominant, co-dominant, and suppressed individuals. The same ground area can be colonized by either many small trees or a few large trees. In the case of beech, there are more than 300,000 seedlings/ha in a natural regeneration, which decrease to about 300 stems/ha at 120 years of age.

Despite all the connections between trees via roots or via mycorrhizal fungi, weaker trees continuously die (the process is called self-thinning). Only the tallest and most vital trees survive. In this process, the living portion of wood in the roots and in sapwood increases in proportion to the leaf mass [22]. In beech, the living biomass in the wood (sapwood biomass) increases from about 40 t $C_{sapwood}$ ha^{-1} at age 30 to about 140 t $C_{sapwood}$ ha^{-1} at age 120, and at the same time the leaf mass decreases from about 2 t C ha^{-1} in the 30-year stand to about 1 t C ha^{-1} in the 140-year stand [23]. Thus, the ratio of respiring tissues to photosynthesizing tissues steadily increases while increment decreases. Changes in wood supply correspond to increment minus all losses due to dieback or utilization.

and the diligence and establishment of the local countryside of how a conversation and cultivation of the wood should be that there is a continuous, steady, and sustainable use, which is an indispensable requirement without which the country may not remain in its essence." The aim of Carlowitz was to provide so-called pit timber for mining, which secured the shafts of the Duke of Saxony. Carlowitz does not say anything about the stocks to be aimed for. It was only specified that the utilization should not exceed the increment at the enterprise or landscape level. Thus, the wood stocks at the landscape level are kept constant. This concept deals not with the life of a single tree, but with forest stands at landscape level. The level of stocks anticipated is determined by the products to be harvested at the landscape level.

The causes for the observed increases and decreases of wood stocks in the forest are manifold. Primarily, the age-structure and tree species composition have an effect. In addition, site and environmental conditions, calamities, and high or low market prices influence the level of pre- and end-use and thus the stand stocks. In general, the older and higher stands with high wood stocks are more vulnerable to biotic and abiotic risks (wood rot fungi, bark beetles, wind breakage). Against this background, forest owners make their decisions starting from a management plan which is an expert report for properties that are smaller than 50 ha, and on proper forest management plans for properties that are larger than 100 ha. These management plans regulate the production and use over a period of 10 years and these plans are subject to a sovereign audit. Overexploitation is thus prevented. There is no compulsion for harvest. As a rule, the objectives of forestry operations do not coincide with the objectives of option 1, which is to increase stocks alone. Rather, it is the objective of the overwhelming majority of owners to generate income as a result of sustainable management.

Stand stocks and soil carbon in managed and protected unmanaged forests.

A comparison of the maximum and mean timber stocks in German forests on managed and protected areas (Table 1) provides information on the actual real potential of both forms of utilization. Coniferous forests have higher average usable stocks than deciduous forests. In spruce stands, there are no statistical differences in the mean and maximum stocks of managed and protected stands. In deciduous forests, the mean stocks are lower when managed, but the maximum stocks at the time of harvest do not differ between managed and unmanaged stands.

TAB 2. AVERAGE AND MAXIMUM STAND VOLUMES, AVERAGE AREA-WEIGHTED STAND AGES AND GROWTH IN MANAGED AND PROTECTED DECIDUOUS AND CONIFEROUS FORESTS [7]

	deciduous forest (beech)			coniferous forest (spruce)		
	protected	managed	significance	protected	managed	significance
Mean stocks (wood volumes) (m^3 ha^{-1} living&dead wood)	435 ± 34, n = 332	366 ± 6, n = 9104	***	421 ± 37, n = 308	425 ± 6, n = 15073	n. s.
Maximum stand stock (m^3 ha^{-1} living&dead wood), from including 95.percentile	981 ± 148, n = 46 from 732	919 ± 195, n = 776 from 15519	n. s.	1118 ± 202, n = 43 from 859	1098 ± 201, n = 1456 from 29113	n. s.
Area weighted age	115	101		94	69	
Wood increment (m^3 ha^{-1} $year^{-1}$)	8,99 ± 0,9, n = 327	10,28 ± 0,16, n = 8746	***	9,01 ± 1,04, n = 271	13,95 ± 0,16, n = 14219	***

TAB 2. C-STOCKS IN GROUND UP TO 1 M DEPTH IN NON-MANAGED AND ADJACENT MANAGED PARCELS OF OLD PROTECTED AREAS OF EUROPE

soil layer	location	number of sites	not managed	managed	significance
Org. circulation (t C/ha)	Fontainbleau	20	11,3 ± 7,3	7,0 ± 4,4	n. s.
	Bialowieza	20	6,2 ± 4,1	20,3 ± 11,4	n. s.
	Hainich	465	7,2 ± 4,5	5,3 ± 3,5	n. s.
	Soil Condition Survey	41 protected 156 managed	15,8 ± 19,7	13,5 ± 25,1	n. s.
Mineral soil (t C/ha)	Fontainbleau	20	35,5 ± 6,1	32,0 ± 5,9	n. s.
	Bialowieza	20	59,5 ± 18,2	66,9 ± 8,9	n. s.
	Hainich	465	102,9 ± 20,8	98,5 ± 27,3	n. s.
	Soil Condition Survey	41 protected/156 man.	80,3 ± 41,0	81,1 ± 40,1	n. s.

Source: Various studies by MPI-Biogeochemistry in deciduous forests and the Thünen Institute in beech stands and according to the results of BZE II in Germany.

There is a significant difference between managed and protected forests in the increment. Managed forest have higher increments, which is equivalent to a higher contribution to climate change mitigation if used. A reduction in use leads to economic displacement processes, whereby the demand for wood is met by imports from other regions of the world, whose sustainability standards are often lower, or the wood is replaced by other materials that are more emission-intensive in their production.

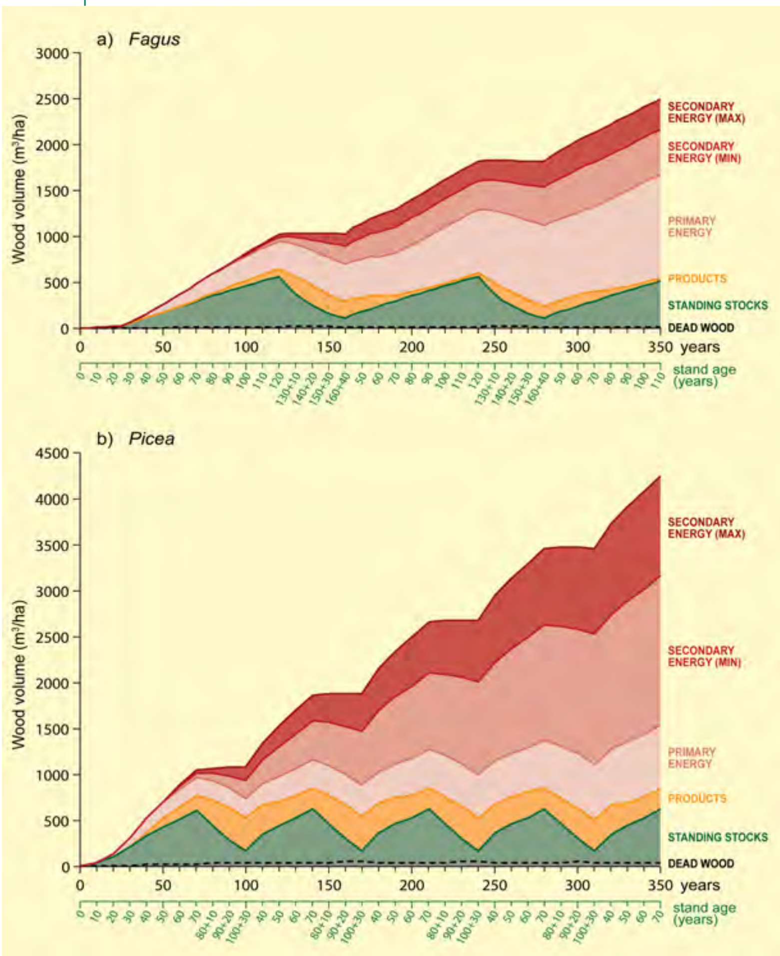
Carbon is stored not only in the wood, but also in the mineral soil and in the overburden humus, with the higher proportion stored in the mineral soil. There are no significant differences between managed and protected stands, neither in the organic layer nor in the mineral soil (Table 2). This contradicts studies that were done on individual experimental plots [9], but do not represent conditions at the landscape level. The second forest soil survey (BZE-II) in Germany shows that soil carbon in forests is increasing under current management (about 0.41 t C ha^{-1} $year^{-1}$) [10].

Storage of carbon in wood products and product substitution (option 3)

Processing of wood has two effects on climate mitigation: (1) it affects the amount of carbon that is fixed in wood products (product storage), and (2) it substitutes materials that require more fossil energy in their production than wood products (product substitution, material substitution). According to current international agreements, only the product pool is currently counted as a contribution of the forest and wood sector to climate protection. Product substitution is quantified as a decrease in the consumption of fossil fuels, but is not reported as such, or even credited in favor of the forest and wood sector. Wood products encompass a wide spectrum of uses, ranging from construction lumber to furniture lumber to toilet paper (Figure 1). In addition to use as sawlogs, lower quality wood and wood waste from processing (e.g., sawdust) are converted into particleboard or used for energy. Of the softwood, 84 percent is currently used as material in the first processing stage, while the majority (70 percent) of the hardwood is used directly for energy [11-13]. The aim is to achieve cascade utilization, in which wood is reused for various products in several stages and is only used for energy at the end of this utilization chain. The aim is to increase product storage in the future in order to bind the carbon stored in it, which was removed from the atmosphere via photosynthesis, for a longer term and in larger quantities.

An important parameter for assessing the effectiveness of product storage is its average time of use.

FIG. 4 | LIFECYCLE OF BEECH AND SPRUCE



Shown are the changes in stand biomass, products and energy wood over the life cycle of the two tree species. All parameters (including energy) are converted to wood volumes to be comparable with forest stocks and increments. Beech has a higher weight per volume than spruce and is thus underestimated. Product substitution is not shown because of uncertainties in coverage. For energy use, a distinction is made between primary energy (firewood) and secondary energy (waste materials and objects after their use). Since energetic substitution cannot be reversed, the effects add up in the savings of fossil energy sources. In the long term, energy substitution makes a significantly greater contribution to climate protection than the forest stand itself. Fig. according to [19].

For products made from beech wood, due to the currently high proportion of firewood, the average life span of three years is lower than the average time taken for beech wood to rot in the forest (11 years). For spruce, the decay rates of products and decaying logs are the same (22 years). Softwood decays more slowly, and it is stored in used form longer than hardwood [11]. Examination of the life cycle of wood (Fig. 4) shows that product storage (amount of wood in product form) remains nearly constant over longer periods of time with current use. The product store is an intermediate store before the final energy recovery.

Increasing product pool offsets greenhouse gases in the atmosphere without directly reducing fossil fuel consumption.

In principle, all wood products can also be manufactured from other materials. The buyer decides whether wood or another material is used. However, the use of wood products avoids the use of materials that require more energy to manufacture (product substitution). For example, the production of a wooden house requires 35 to 50 percent less energy than a functionally equivalent solid construction [2]. Product substitution is estimated using a factor that describes the savings in carbon emissions (in tons of carbon) per ton of carbon in the wood product. The average substitution factors determined so far [14-16] are between 1.2 and 2.1 t C/t C and have a high degree of uncertainty. Based on these factors, between 28 and 53 million tons of $CO_{2\text{-equiv}}$ from fossil sources are avoided annually in Germany. This is 2.8 to 4.9 $CO_{2\text{-equiv}}$ ha^{-1} $year^{-1}$, including fossil fuel consumption during processing. Product substitution is not reported in the greenhouse gas balance according to the IPCC guidelines [5]. Product substitution reduces fossil fuel consumption and thus has a different quality than storage. The production of new materials from wood based on gasification of the biomass or restructuring of the cellulose was not considered here.

Energetic use of biomass (option 4)

The use of wood as fuel is one of the oldest uses by humans. Even today, a relatively large amount of wood is used directly for energy (firewood, wood chips, pellets). Residual and waste materials from wood processing are also used for energy (e.g. in drying plants), as are wood products after use.

TAB 3. WOOD BALANCE OF GERMANY

	(million m^3/year)	%
Forest growth in Germany	121.6	100
Change in stocks of inventories	15.3	13
Deadwood in the forest	10.4	9
Logging residues of the felling	10.1	8
Bark & oversize during sales of wood	10.1	8
Firewood	19.7	16
Industrially used wood	56.0	46
	(m^3_{diesel} ha^{-1} $year^{-1}$)	(t CO_2 ha^{-1} $year^{-1}$)
Substitution of energy-rich products	1.1 to 1.9	2.8 to 4.9
Substitution of fuel oil by wood combustion	1.1 to 1.2	2.9 to 3.2

Green: amount of wood grown in the forest, Red: wood utilization, Yellow: climate effects taking into account the consumption of fossil fuels in wood harvesting and wood processing [12].

The energy recovery from products after use is only partially successful, e.g. via bulky waste or waste wood from building renovations. Other wood products rot on site, such as a fence post in a meadow. Currently, only about 54 percent of wood products are used for energy [11]. A quantification of the energy wood volumes is problematic because some of the wood harvested is not recorded and it is transported out of the forest with the wood as an "addition" during wood sales (bark, oversize). Another part is harvested for private use and is not statistically taken into account [11]. The official "logging statistics" are therefore incomplete. Of the total annual increment, more than 70 percent is used in the German forest. The share of industrial use in the total annual increment is about 46 percent.

In the discussion about the use of wood as an energy source, it is often argued [17, 18] that wood has a lower energy density than fossil fuels and would therefore pollute the atmosphere more than the use of fossil fuels. This neglects the fact that in sustainably managed forests, the emitted CO_2 is recaptured in the foreseeable future, whereas a new formation of fossil fuels takes millions of years. Due to ecosystem respiration, about 74 to 94 percent of the photosynthetically bound carbon is degraded by microbes in protected forest compared to 75 to 81 percent in the managed forest in a relatively short time. The decomposition of dead wood and the decomposition of logging residues (twigs and branches) during management feed the ecosystem. Through energetic wood utilization, the chemically bound energy in the wood is not used by microorganisms, but by humans. This is the only way to replace energy-rich fossil fuels. This accounts for almost 10 percent of the total CO_2 cycle. The emissions from biomass combustion are offset by lower ecosystem respiration. Forest management and wood use currently improve Germany's annual greenhouse gas balance by about 11-14 percent, which is divided approximately equally between forest storage (living and dead biomass and forest soil) and wood use (product storage, material and energy substitution).

The use of forest land for wind power and solar installations (option 5)

Photosynthesis uses about one percent of the incident solar energy. This is about 4 percent of the power that could be generated on the same area by wind turbines and 0.1 percent of the power that could be generated by solar plants [11]. Under laboratory conditions, solar cells are able to use up to 34 percent of the sun's energy. In order to achieve the ambitious climate protection goals in Germany, the question therefore arises as to whether forest areas should not be converted for this purpose for the construction of wind power and solar plants (option 5).

The expansion of wind turbines in forests primarily affects wildlife (especially insects, bats and birds) and the landscape. The land consumption is comparatively low, but should not be underestimated [11]. Solar plants would technically make more sense, but require the clearing of existing forest with a loss of habitats for plants and animals. They are therefore viewed rather critically. Economically, however, these alternative forms of land use will remain interesting for the owner until they are adequately remunerated for the ecosystem services beyond the use of wood. The discussion has therefore not yet been concluded.

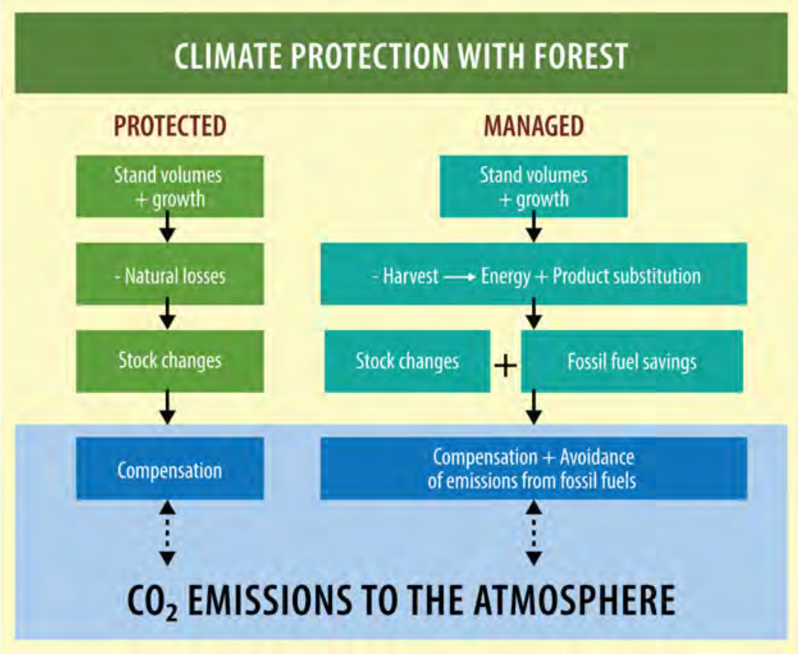
CONCLUSION

The official climate protection-accounting for forests is incomplete. The importance of forest management and wood use for climate mitigation is not considered (Figure 5). The abandonment of wood uses ("set-aside of forest use") to further expand the carbon store in the forest is associated with high risks and is not sustainable. There are additional displacement effects from forest use in forests outside Germany to meet the demand for wood. The provision of wood for woodworking and processing industries enables the use of wood products as a substitute for construction and other uses that are more energy-intensive to produce and cause higher emissions (material substitution). The energetic use of wood replaces fossil fuels (energetic substitution) and, in the case of sustainable forest management, does not additionally burden the atmosphere because the carbon bound in the wood is alternatively released through decay. Up to now, material and energetic substitution have not been recognized as a forest management service. The demand for recognition of these services was already made in 1999 [17, 18]. If forests were converted, for example, into solar plants, the efficiency of energy production per hectare of land would increase considerably, but many ecosystem services of the forest would be drastically impaired. Provided that the land use of forest areas is not changed, sustainable management and the material and energy use of the wood harvested in these processes will make a greater contribution to climate protection in the long term than natural forest development without wood utilization.

Summary

Options for the forest's contribution to climate protection follow the path of wood from the forest to energy recovery. Sustainably managed forests can avoid 6 to 8 tons of CO_2 ha^{-1} $year^{-1}$ emissions from fossil fuels by providing wood, while unmanaged forests offset emissions from fossil fuels by storing carbon in the ecosystem, but do not save fossil fuels.

FIG. 5 | FOREST PERFORMANCES FOR CLIMATE MITIGATION



Summary

Climate mitigation by forests

This is an overview of options by which forest management contributes to the mitigation of climate change effects. We follow the wood from harvest to its final energy use. By sup- ply of wood, forest management can substitute 6 to 8 tons CO_2 $ha^{-1}yr^{-1}$ of fossil fuel emissions while under non-management conditions storage of carbon compensates fossil fuel emissions without reducing fossil fuel use.

KEYWORDS:

Product substitution, energy substitution, carbon sequestration, emissions accounting, climate impact.

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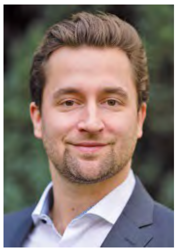
The authors


Prof. emeritus Dr. Dr. h. c. Ernst Detlef Schulze studied forestry and biology, worked as a professor of plant ecology at the University of Bayreuth before becoming the founding director of the Max Planck Institute for Biogeochemistry in Jena.


Dr. Joachim Rock works at the Thünen Institute for Forest Ecosystems in Eberswalde in the field of Greenhouse Gas Monitoring. He studied forestry, holds a PhD in geoecology and has been working on greenhouse gas accounting, climate change and forest management for 20 years.


Franz Kroiher studied forestry and is a cross-sectional conservation officer at the Thünen Institute for Forest Ecosystems in Eberswalde.


Vincent Egenolf is a research associate at the Center for Environmental Systems Research (CESR) at the University of Kassel. He studied biology and bioeconomics and is currently investigating the forest footprint of the German bioeconomy and its impacts.


Dr. Nicole Wellbrock heads in the Thünen Institute. for forest ecosystems the soil survey in forests. She studied geography with a focus on soil science and did her PhD on critical loads for nitrogen deposition.


Prof. (ret.) Roland Irslinger studied forestry, worked as a professor of ecology at the University of Applied Forest Sciences in Rottenburg am Neckar, established a site mapping in Brazil, and founded a professorship for ecobalancing and climate change in Rottenburg.


Prof. Dr. Andreas Bolte studied forestry, is an adjunct professor of forest ecology at the University of Göttingen and heads the Thünen Institute for Forest Ecosystems.


Prof. Dr. Hermann Spellmann was head of the Nordwestdeutsche Forstliche Versuchsanstalt (Northwest German Forest Research Institution) until March 31, 2020, taught in the Department of Silviculture and Forest Ecology of Temperate Zones at the University of Göttingen, and was chairman of the Scientific Advisory Board for Forest Policy at the Federal Ministry of Food and Agriculture until December 31, 2019.

Correspondence:
Prof. Dr. Dr.h.c. Ernst Detlef Schulze
Max Planck Institute for Biogeochemistry P.O. Box 100164
07701 Jena
E-mail: dschulze@bgc-jena.mog.de