https://doi.org/10.17221/74/2024-JFS

Carbon storage and climate mitigation effect in Central European forestry – To be managed, or left unmanaged?

Michal Synek[1], Emil Cienciala[2], Jaroslav Kubišta[1]*

[1]*Forest Management Institute (FMI), Brandýs nad Labem, Czech Republic*
[2]*Institute of Forest Ecosystem Research (IFER), Jílové u Prahy, Czech Republic*

**Corresponding author: Michal.Synek@nli.gov.cz*

Citation: Synek M., Cienciala E., Kubišta J. (2025): Carbon storage and climate mitigation effect in Central European forestry – To be managed, or left unmanaged? J. For. Sci., 71: 149–158.

Abstract: This study investigates differences in carbon storage between managed and unmanaged forests in the growth conditions of Central Europe. Norway spruce (*Picea abies*), European beech (*Fagus sylvatica*) and pedunculate oak (*Quercus robur*) dominated forest types were considered, as these are the most common forest species in the Czech Republic. Scots pine (*Pinus sylvestris*), as the second most common species, was excluded due to lacking relevant reference data on unmanaged forests. Managed and unmanaged variants of each forest type were assessed in terms of carbon sequestered in biomass, dead wood and harvested wood products (in the managed variant). Harvested wood products yielded during two rotation periods were considered, including their substitution effect as well as respiratory losses, to fully assess their contribution to carbon balance. Average carbon storage in the above-ground biomass and deadwood was lower in the managed forest compared to the unmanaged forest in comparable growth conditions. However, this difference is in our model examples compensated by carbon stored in the harvested wood products including their substitution effect in the managed forests of Norway spruce and pedunculate oak. Contrarily, managed European beech forests showed, in our case, slightly lower carbon storage compared to the unmanaged alternative. The estimates for all species are considered to be rather conservative due to the assumed factors affecting the results. Due to generally limited comparative data on unmanaged forests in the region, the results should be interpreted with caution.

Keywords: CO_2 emission offset; displacement effect; harvested wood products; increment; substitution effect; tree biomass; wood production

In the context of decarbonization and emission reduction targets adopted by the European Union, the interest in evaluating the climate mitigation potential of forests and forestry has been increasing. The most recent European policies related to the landscape and forestry sector (LULUCF – land use, land-use change and forestry) such as the revised LULUCF regulation (EU Regulation 2023/839) and the EU Forest Strategy for 2030 (EC 2021) link the climate mitigation (CO_2 sequestration) with the other vital forest ecosystem services and benefits to society, such as wood production, water retention, local microclimate, soil protection, hosting biodiversity and recreation. This makes strategic forestry planning more complex. It must optimise societal demands on the existing forest resources and their biological potential while considering adaptive management strategies to address likely challenges associated with the progressing climate change (Kallio et al. 2023; Korosuo et al. 2023).

Climate change poses a serious threat to life on Earth. Numerous activities are being carried out to mitigate climate change with a focus on re-

© The authors. This work is licensed under a Creative Commons Attribution-NonCommercial 4.0 International (CC BY-NC 4.0).

https://doi.org/10.17221/74/2024-JFS

ducing the cause of global warming – greenhouse gases in the atmosphere. Apart from decreasing the emissions of greenhouse gases, sequestration of existing greenhouse gases from the atmosphere is considered an important part of the possible solution. In this respect, forests are expected to play a crucial role in the sequestration of carbon dioxide from the atmosphere and to act as a carbon reservoir (Grassi et al. 2017; Lindroth, Tranvik 2021; Roe et al. 2021).

While the importance of non-productive forest functions and services has been steadily increasing in recent decades, forest policies must primarily evaluate the effect of production function which remains pivotal in the self-sustained economy of any forest owner.

In the context of the increasing global greenhouse gas emissions reaching 35.8 Gt CO_2 eq. in 2023 (Liu et al. 2024), all processes and mechanisms reducing emissions or increasing carbon sinks have become increasingly valuable. Wood is a key outcome of carbon dioxide sequestration. The global average annual production of harvested wood products in the period from 1992–2015 is estimated to account for 0.277 Gt (gigatons) of carbon (C) (Zhang et al. 2020) which highlights the importance of active forest management.

For comparison, a total amount of 226 Gt C was recently estimated as the current global potential for forest vegetation to sequester additionally, once the protection and restoration measures are fully implemented (Mo et al. 2023). This figure is by several orders higher, as it represents the potential total additional amount to be reached over a long period. Also, the authors of the above study explicitly note that the role of active forest management cannot be disregarded and should be considered for its substitutional function in providing woody products that are emission less-intensive as compared to their alternatives. This effect is called the substitution or displacement effect (Leskinen et al. 2018; Howard et al. 2021), and it is accounted for by appropriate factors.

The carbon balance-related impacts of the decision to prioritise active forest management or leave the forest to spontaneous development need to be better evaluated and understood. Therefore, this study aims to provide estimates showing the effects of active forest management on carbon stock in comparison with unmanaged forests in Central European forestry.

MATERIAL AND METHODS

The research aims to compare the carbon balance of an unmanaged forest stand left to develop spontaneously with a forest stand managed in the standard way for two rotation periods. The comparison used three main tree species occurring in the Czech Republic: Norway spruce (*Picea abies*), European beech (*Fagus sylvatica*), and pedunculate oak (*Quercus robur*). Scots pine (*Pinus sylvestris*) was not included in the analysis because there are no unmanaged Scots pine stands documented in detail in the country. In managed forests, the carbon balance of the stand includes wood products produced during both rotation periods and their substitution factor. The rationale behind the selection of two rotation periods is that we study products with carbon dynamics exceeding the duration of a single rotation period. The substitution factor indicates the amount of carbon emissions that can be avoided by using wood instead of greenhouse gas-intensive materials.

Unmanaged forest. To model the unmanaged forest stand, we referred to publications that focus on the dynamics of primary forest reserve development in the Czech Republic (Vrška 2002, 2006). The publications were used to select primary forest reserves dominated by Norway spruce, European beech and pedunculate oak. For each selected primary forest reserve, the growing stock of living and dead trees per ha was determined based on average values. This approach is based on the assumption that all growth stages (stage of growth, stage of optimum and stage of disintegration) are present simultaneously. A stable average growing stock of living and dead trees is assumed for the whole period (Table 1).

The amount of carbon stored in the living trees was calculated using the Intergovernmental Panel on Climate Change (IPCC) reporting methodology and national coefficients for specific tree species (CHMI 2023). To calculate the biomass, we used biomass conversion and expansion factors (BCEF) for the aboveground biomass (Norway spruce – 0.555; pedunculate oak – 0.813; European beech – 0.699) and root/shoot ratio for the belowground biomass (Norway spruce – 0.21; pedunculate oak – 0.23; European beech – 0.23). The biomass was then converted to carbon using a fraction of carbon 0.508 and 0.488 for coniferous and broadleaved tree species, respectively (Thomas, Martin 2012). The same

https://doi.org/10.17221/74/2024-JFS

Table 1. Selected primary forest reserves and their growing stock characteristics (Vrška 2002, 2006)

Forest reserve	Tree species	Share of growing stock (%)		Growing stock per volume ($m^3 \cdot ha^{-1}$)		
		live trees	dead trees	live trees	dead trees	total
Polom nature reserve	Norway spruce	70.3	24.1	593	138	731
Cahnov-Soutok national nature reserve	pedunculate oak	35.2	80.9	549	133	682
Žákova hora national nature reserve	European beech	60.3	57.8	580	133	713

approach was used for dead wood, but the amount of carbon was reduced to 50% because it was assumed that on average, half of the dead wood was decayed.

Managed forest. The development of a managed forest was modelled for both rotation periods using compound forest figures from yield tables valid for the Czech Republic (Černý, Pařez 1996). Corresponding to the selected primary forest reserves, average absolute height classes were used for modelling the growing stock development, with Norway spruce at 32, pedunculate oak at 30, and European beech at 30. Thinning and felling intensities defined in Decree No. 84/1996 were applied to the related age classes to derive the amount of wood removals. The initial growing stock of a particular age class was reduced by the harvested volume, and the increment percentage was applied to the remaining growing stock. The amount of deadwood was estimated to be 10% of wood removals as the information on the distribution of deadwood by age class and tree species was not available. The amount of carbon stored in the living trees and dead wood was calculated using the same methodology as for the unmanaged forests, only age-class-based BCEFs were used. An area-based approach was also applied, assuming that all age classes were available simultaneously and occupied the same area.

The potential amount of industrial roundwood and pulpwood for further wood processing was calculated based on wood removals, using the shares of industrial roundwood and pulpwood defined in the assortment tables (Simanov 1996) for the average qualities of particular tree species. For sawlogs and veneer logs, average shares of products and co-products for the conditions of the Czech Republic were used, considering the tree species group, as stated in Table 2. In the case of pulpwood, we assumed a 10% loss, with the remaining amount divided between pulp and wood-based panel production. Considering the wood processing capacities of coniferous and non-coniferous tree species in the Czech Republic, we allocated 68% for pulp production and 32% for wood-based panel production to both tree species groups. Wood chips, which are co-products from the sawmill industry, are also processed for pulp production.

Wood fuel, logging residues and wood pellets produced from sawdust in sawmills are also considered wood products.

In order to assess the carbon balance of wood products comprehensively, we also included their substitution effect in the calculation. The substitution factor for wood products, also known as the displacement factor, is a unitless ratio that measures the reduction of greenhouse gas emissions achieved by using a wood-based product instead of an alternative product that serves the same purpose (Leskinen et al. 2018). An equation of the substitution factor (*SF*) calculation was introduced by Sathre and O'Connor (2010) and is presented below as Equation (1):

$$SF = \frac{GHG_{\text{other}} - GHG_{\text{wood}}}{WU_{\text{wood}} - WU_{\text{other}}} \tag{1}$$

where:

GHG_{other} – emissions resulting from the use of other material (mass units of C);

GHG_{wood} – emissions resulting from the use of wood alternatives (mass units of C contained in wood);

WU_{wood}, WU_{other} – amounts of wood used in wood and non-wood alternatives, respectively.

The positive value indicates that using a wood product results in lower *GHG* emissions compared to using a non-wood product. The value of the substitution factor depends on the type of non-wood

https://doi.org/10.17221/74/2024-JFS

Table 2. Shares of harvested wood products and co-products (HWP)

Assortment	HWP	Conifers (%)	Broadleaves (%)
Sawlogs	sawnwood	60	50
	chips (paper)	25	30
Pulpwood	panels	29	29
	pulp (paper)	61	61

product that is being replaced by a wood product and on the life cycle stages that are taken into account during the calculation. The average substitution effect of 1.2, as reported in Leskinen et al. (2018), was applied to all wood products produced from managed forests at the time of production.

In accordance with the IPCC reporting guidelines (IPCC 2006), respiratory losses were applied to sawnwood, wood-based panels, paper and paperboards, with half-lives of 35, 25 and 2 years, respectively. For wood fuel, a half-life of 3 years was used. Logging residues and wood pellets were assumed to be used shortly after production and therefore respiratory losses were not applied.

The cascade of removals processed into further products is visualised in Figure 1.

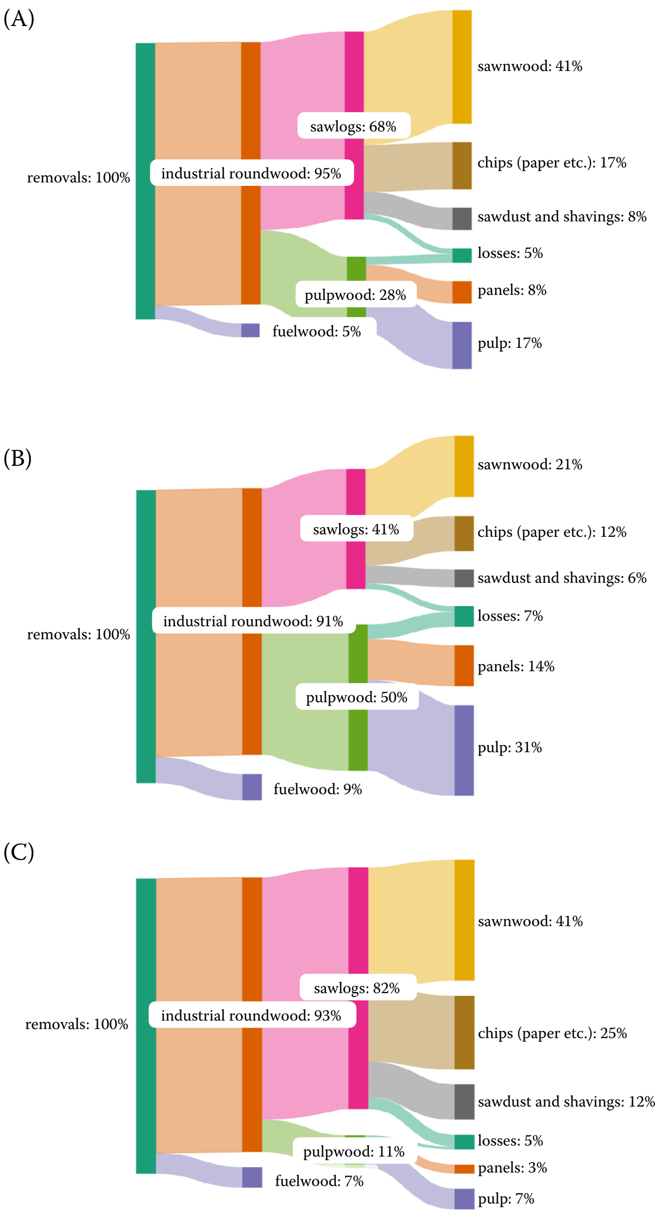

Figure 1. Processing removals for the main tree species: (A) Norway spruce, (B) pedunculate oak, and (C) European beech

https://doi.org/10.17221/74/2024-JFS

RESULTS

The unmanaged mixed Norway spruce forest reaches an equilibrium of 592 m^3 u.b.$\cdot ha^{-1}$ of growing stock and 137 $m^3 \cdot ha^{-1}$ of dead wood. When converted to the biomass and carbon content, the unmanaged Norway spruce forest sequesters an average of 215 t $C \cdot ha^{-1}$. In comparison to this, the managed Norway spruce forest, modelled as even-aged stands, sequesters on average 155 t $C \cdot ha^{-1}$ in the aboveground biomass and deadwood. Additionally, 45 t C is sequestered in the harvested wood products (HWP), including the consideration of respiratory losses. This figure is partially influenced by the production of the HWP produced in the first rotation period. Additionally, the substitution effect of the produced wood products amounts to 24 t C. The managed Norway spruce forest, in our case, has an overall sequestration effect of 224 t $C \cdot ha^{-1}$, which is 9 t $C \cdot ha^{-1}$ more than the unmanaged Norway spruce forest.

The distribution of carbon storage in the particular age classes of managed forest compared to average values both of managed and unmanaged forest stands is presented in Figure 2.

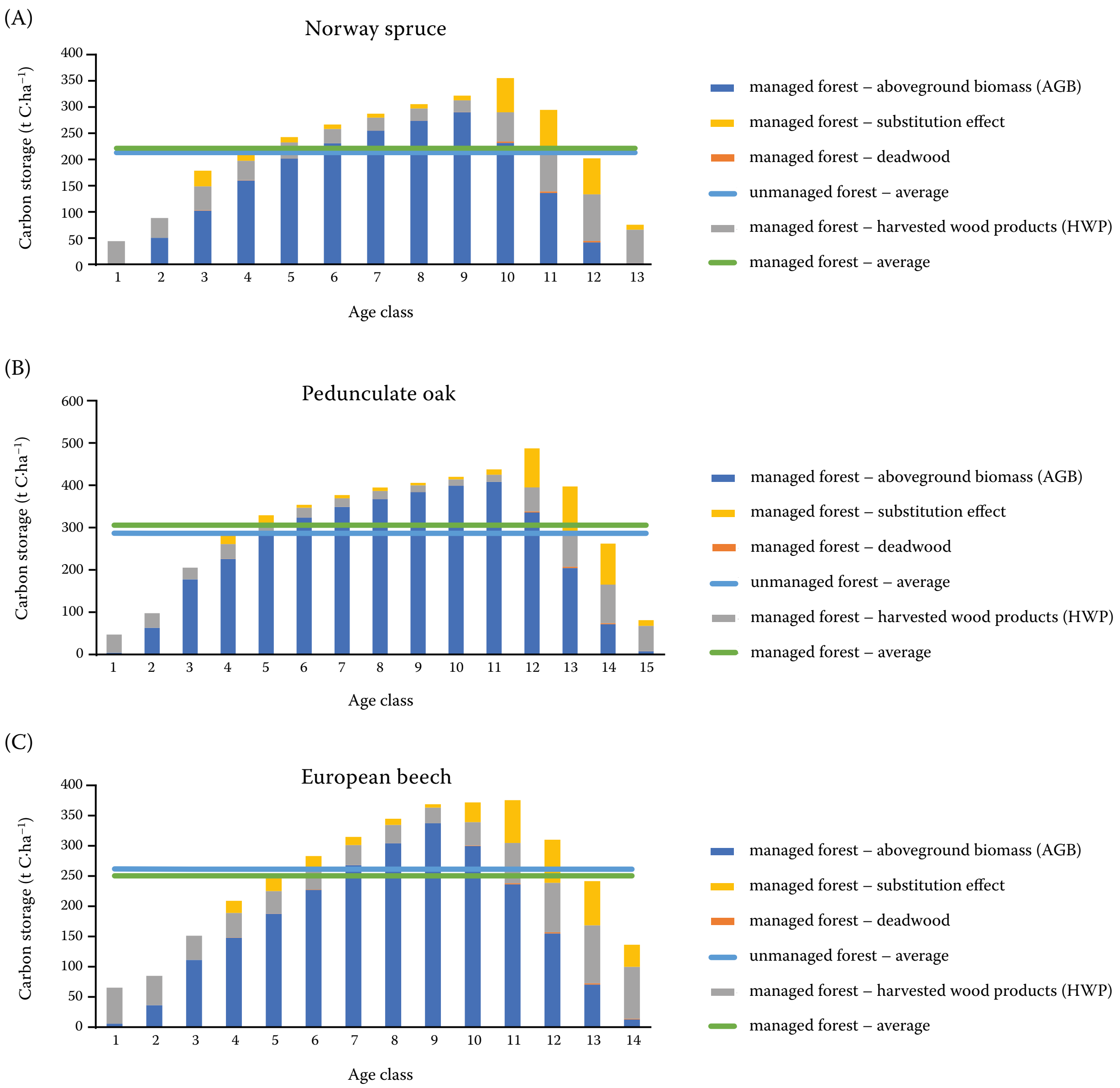

Figure 2. Carbon storage in particular age classes (10 years each) of managed forest compared to average values both of managed and unmanaged forest: (A) Norway spruce, (B) pedunculate oak, and (C) European beech

https://doi.org/10.17221/74/2024-JFS

The unmanaged mixed pedunculate oak forest reaches an equilibrium of 549 m^3 u.b.·ha^{-1} of growing stock and 133 m^3·ha^{-1} of dead wood. When converted to biomass and carbon content, the unmanaged pedunculate oak forest sequesters on average 288 t C·ha^{-1}. The managed pedunculate oak forest, modelled as even-aged stands, sequesters on average 242 t C·ha^{-1} contained in the aboveground biomass and deadwood. Additionally, 38 t C is sequestered in harvested wood products (HWP), including the consideration of respiratory losses. This figure is partially influenced by the HWP produced in the first rotation period. Additionally, the substitution effect of wood products amounts to 27 t C. The managed pedunculate oak forest, in our case, has an overall sequestration effect of 307 t C·ha^{-1}, which is 19 t C·ha^{-1} more than the unmanaged pedunculate oak forest.

The unmanaged mixed European beech forest reaches an equilibrium of 580 m^3 u.b.·ha^{-1} of growing stock and 133 m^3·ha^{-1} of dead wood. When converted to biomass and carbon content, the unmanaged European beech forest sequesters on average 263 t C·ha^{-1}. The managed European beech forest, modelled as even-aged stands, sequesters on average 174 t C·ha^{-1} in the aboveground biomass and deadwood. Additionally, 51 t C is sequestered in harvested wood products (HWP), including the consideration of respiratory losses. This figure is partially influenced by the HWP produced in the first rotation period. Additionally, the substitution effect of wood products amounts to 27 t C. The managed European beech forest, in our case, has an overall sequestration effect of 252 t C·ha^{-1}, which is 11 t C·ha^{-1} lower than the unmanaged European beech forest. The overview of all variants is summarised in Table 3.

DISCUSSION

Data from specific individual forest reserves, which are generally mixed stands dominated by the selected main tree species, have been compared with even-aged and homogeneous managed forests modelled using yield tables valid for the Czech Republic (Černý, Pařez 1996). Thinning and felling intensities for even-aged stands defined in Decree No. 84/1996 of the Forest Act were then applied to the related age classes to derive the amount of wood removals. This methodological approach was selected due to the fact that according to results of the National Forest Inventory (Kučera, Adolt 2019), stands with a simple structure still dominate in the Czech Republic, while data for long-term development of mixed or uneven-aged stands are not available in adequate detail and amount. We are aware of possible uncertainties associated with this approach, but our objective was to obtain robust estimates using the current knowledge and the best available data. A comparable approach was employed by Schulze, Stupak and Hessenmöller (Schulze et al. 2019), who utilised yield tables to simulate the growth of managed forests. Forest growth data from unmanaged forest remnants in the Czech Republic and Slovakia gathered by Korpel (1989) were used for the purpose of modelling the growth of unmanaged forests.

Our results do not support the idea that harvesting can stimulate tree growth over the long term compared to unmanaged forests as it is presented, for example, by Landry et al. (2021). Average carbon storage in aboveground biomass and deadwood is, in our results, lower for the managed forest compared to the unmanaged forest. However, this dif-

Table 3. Comparison of carbon storage

Forest type	Carbon pool	Norway spruce	Pedunculate oak	European beech
		tonnes of carbon per ha (t C·ha^{-1})		
Unmanaged forest	aboveground biomass	201	268	244
	deadwood	14	19	19
	total	215	288	263
Managed forest	aboveground biomass	154	241	173
	deadwood	1	1	1
	HWP	45	38	51
	substitution effect	24	27	27
	total	223	307	252

HWP – harvested wood products

https://doi.org/10.17221/74/2024-JFS

ference is sufficiently outweighed by carbon stored in the harvested wood products and by the substitution effect of these. Schulze et al. (2019) observed comparable outcomes for Norway spruce and European beech. For Norway spruce, over a 350-year projection period, the biomass stocks averaged 349 $m^3 \cdot ha^{-1}$ under managed conditions and 406 $m^3 \cdot ha^{-1}$ under unmanaged conditions. However, after incorporating wood products, the managed alternative reached 624 $m^3 \cdot ha^{-1}$. That positive effect was also demonstrated in the case of European beech. In this instance, the stocks were found to be lower, at 279 $m^3 \cdot ha^{-1}$ in managed European beech versus 324 $m^3 \cdot ha^{-1}$ in unmanaged European beech. However, following the inclusion of wood products, the managed alternative reached 543 $m^3 \cdot ha^{-1}$.

For unmanaged forests, it is assumed that all growth stages (stage of growth, stage of optimum and stage of disintegration) are present simultaneously. The stage of disintegration, particularly in the case of Norway spruce, can spread easily over large areas and cause a significant reduction in carbon stock due to the loss of increment and decay of dead wood. The difference between the average value and the stage of disintegration is 36 t $C \cdot ha^{-1}$ in the selected Norway spruce reserve.

Our results show that the mitigation potential of forests can be enhanced by active forest management and the use of harvested wood products. This enhancement can be further supported by maximising the use of wood products with a longer life cycle, such as construction wood etc. Similar results, underlining the impact of different harvested wood use on carbon balance and the necessity to prolong the wood products' life cycle, were reported by Valade et al. (2017). Schulze et al. (2019) compared managed and unmanaged Norway spruce and European beech forests in Germany and found that managed forests provide greater climate benefits, particularly when wood is used as a substitute for fossil fuels and fossil extensive materials. The study showed that managed Norway spruce forests contribute more to climate change mitigation than managed European beech forests.

The substitution factor for wood products depends on the type of non-wood product that is being replaced by a wood product and on the life cycle stages that are taken into account during the calculation. According to several authors, there is a high variability and uncertainty in the quantification of substitution factors (Smyth et al. 2017; Leskinen et al. 2018; Kallio et al. 2023). We used the average substitution factor of 1.2 derived by Leskinen et al. (2018), who provided a comprehensive review of substitution factors based on 51 individual studies and many of these studies covered only the production stage. Average substitution factors were also derived by broad product categories and for different life cycle stages.

If we used the substitution factor 2.1 derived by Sathre and O'Connor (2010), the managed European beech forest would achieve a total sequestration effect of 273 t $C \cdot ha^{-1}$, which is 10 t $C \cdot ha^{-1}$ more than the unmanaged European beech forest. Sathre and O'Connor (2010) focused mainly on the construction sector and considered end-of-life stages.

Moreau et al. (2023) used the following substitution factors for the province of Quebec, expressed as the amount of carbon emissions avoided per tonne of biogenic carbon in the wood product: 0.91 t $C \cdot t\ C^{-1}$ for sawnwood and 0.77 t $C \cdot t\ C^{-1}$ for panels and other sawmill products. These substitution factors do not include energy recovery at the end-of-life stage but rather landfilling. Emissions from wood product decay were calculated using a decomposition function with half-life values based on the Intergovernmental Panel on Climate Change (IPCC 2006). An analysis of the substitution factor for non-coniferous sawnwood is missing. The amount of carbon in European beech or pedunculate oak wood is 39% higher than in Norway spruce wood, so the substitution factor should be considerably higher. This could lead to an underestimation of the total sequestration effect of managed European beech and pedunculate oak forests.

Following the IPCC (2006) reporting guidelines, respiratory losses were applied to sawnwood, wood-based panels, paper, and paperboards, with half-lives of 35, 25, and 2 years, respectively. For wood fuel, a half-life of 3 years was used. This approach assumes a gradual release of carbon from these products immediately after production, which is not the case for long-lived products. This methodology neglects recycling and energy recovery of products, despite the fact that both processes have a substitution effect. Iordan et al. (2018) found that assuming all harvested carbon is instantaneously oxidised can lead to large biases and ultimately overlook the benefits of negative emissions of HWPs. They used the product-specific mean

https://doi.org/10.17221/74/2024-JFS

half-life and Chi-square distribution to model the decay. This approach resulted in 64–91% lower carbon emissions per year in the harvested wood products pool in Finland, 49–96% in Sweden, and 6–91% in Norway.

Set aside further forests without management will result in decreased roundwood production leading to roundwood production leakage to other countries. Schulze et al. (2019) stated that in the case of Germany, a forest area 5–10 times larger will be needed to replace roundwood production in the boreal climate zone due to the higher productivity of German forests. Forests in the Czech Republic are equally productive as those in Germany, indicating a similar potential for leakage effects. In the study by Dieter et al. (2020), a possible leakage effect was evaluated for the EU resulting from the fulfilment of the objective of the EU biodiversity strategy for 2030. The study found that the overall roundwood production is expected to decrease by 42% in the EU-27 by 2050. This decrease will be compensated by the increased roundwood production in non-EU countries that have a significantly higher proportion of intact forests compared to the EU. From our point of view, it is also important to consider the higher carbon footprint caused by transporting roundwood over long distances. The potential leakage effect is then an important factor for the preference of active forest management.

This study does not include a scenario outlook that would consider an expected tree species composition change in the Czech Republic. Nevertheless, the positive effect of carbon storage management was confirmed for Norway spruce and pedunculate oak, whereas European beech resulted in slightly lower total carbon storage as compared to the unmanaged option. With the expected increase of broadleaved tree species share in the future, we can only highlight the necessity of proper harvested wood use with the aim to maximise long-term carbon storage in harvested wood products and their substitution effect.

It should be noted that the growth performance and productivity of forest stands have increased in recent decades (Pretzsch et al. 2014, 2023). In the conditions of temperate Europe, this is mainly attributed to a strong fertilisation effect of nitrogen deposition (Kahle et al. 2008; Cienciala et al. 2018), although several other factors linked to the changing climate and rising CO_2 concentration most likely affect the productivity, too. For example, for Scots pine in the temperate region, the growth was reported to increase by 26% from 1975 to 2015 (Pretzsch et al. 2023), while other, more recent studies, suggest that this growth pattern apparently peaked in line with the N-deposition trend and decreased again in recent years (Prietzel et al. 2020). Therefore, the national growth and yield tables for the Czech Republic (Černý, Pařez 1996), which are adopted in the Czech Forest Act and forest planning practice, and which were also used in our analysis to model the development of managed forests, may underestimate the actual increment and our estimates of carbon storage. This underestimation of the real current increment was also confirmed by the Czech National Forest Inventory (Máslo et al. 2023). Specifically, the increment derived from forest management plans using yield tables is, on average, 1.28 $m^3 \cdot ha^{-1}$ lower compared to the National Forest Inventory (NFI) results 2016–2020 (Máslo et al. 2023). This represents a likely underestimation of 15%. Correspondingly, the actual positive effect of forestry on carbon storage may be stronger than indicated by our estimates, which remain rather conservative.

It is important to note that the short-term emission reduction targets set by the EU in its Green Deal policy framework and related regulations, such as EU Regulation 2018/841 and its revision, EU Regulation 2023/839, are in apparent conflict with forestry practice, at least in Central-European conditions. These policies prescribe specific *GHG* emission reduction targets for 2025 and 2030 to be reached by forestry sectors in the Member States (MS). Noncompliance would result in a monetary penalisation in relation to CO_2 units beyond the prescribed threshold. In fact, such a policy commonly contradicts the actual forest practice based on traditional forest management planning and long-term forestry goals, which do not include any specific mitigation targets yet. Hence, these policy goals set at EU and MS levels and their short-time horizons are incoherent with the forestry planning in Central Europe. This issue remains to be addressed for a balanced priority setting in forestry to retain long-term sustainability, prioritising adaptation for the conditions of changing climate. This is the precondition for delivering other expected functions and services expected from forests and forestry, including production and climate change mitigation. Note that

https://doi.org/10.17221/74/2024-JFS

providing these functions is secondary, resulting from – and dependent on – successful adaptation management.

CONCLUSION

Our results indicate that under the specific conditions of Central European forestry, active forest management has a stronger quantitative effect on carbon sequestration and storage as compared to unmanaged forest in the case of Norway spruce and pedunculate oak. Our data did not show this for European beech forest management, which resulted in a slightly lower effect on carbon storage relative to its unmanaged alternative. However, our estimates for all species were rather conservative due to the adopted factors affecting the results (increment and substitution factors for HWP contribution). Hence, our results confirm that at least in the conditions of Central European forestry, active forest management, together with appropriate use of wood products, can serve well as an important climate change mitigation tool, while providing irreplaceable benefits in terms of both wood production and other ecosystem functions.

REFERENCES

Černý M., Pařez J. (1996): Růstové a taxační tabulky hlavních dřevin České republiky: (smrk, borovice, buk, dub). Jílové u Prahy, IFER: 245. (in Czech)

CHMI (2023): National Greenhouse Gas Inventory Report of the Czech Republic. Reported Inventories 1990–2021. Prague, Czech Hydrometeorological Institute: 566. Available at: https://www.chmi.cz/files/portal/docs/uoco/oez/nis/NIR/CZE_NIR-2023-2021_UNFCCC_allinone_ISBN.pdf

Cienciala E., Altman J., Doležal J., Kopáček J., Štěpánek P., Ståhl G., Tumajer J. (2018): Increased spruce tree growth in Central Europe since 1960s. Science of the Total Environment, 619–620: 1637–1647.

EC (2021): New EU Forest Strategy for 2030. Brussels, European Commission: 27.

Dieter M., Weimar H., Iost S. (2020): Assessment of Possible Leakage Effects of Implementing EU COM Proposals for the EU Biodiversity Strategy on Forestry and Forests in Non-EU Countries. Braunschweig, Thünen-Institut: 159.

Grassi G., House J., Dentener F., Federici S., den Elzen M., Penman J. (2017): The key role of forests in meeting climate targets requires science for credible mitigation. Nature Climate Change, 7: 220–226.

Howard C., Dymond C.C., Griess V.C., Tolkien-Spurr D., van Kooten G.C. (2021): Wood product carbon substitution benefits: A critical review of assumptions. Carbon Balance and Management, 16: 9.

Iordan C.M., Hu X., Arvesen A., Kauppi P., Cherubini F. (2018): Contribution of forest wood products to negative emissions: Historical comparative analysis from 1960 to 2015 in Norway, Sweden and Finland. Carbon Balance and Management, 13: 12.

IPCC (2006): 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Geneva, Intergovernmental Panel on Climate Change: 1970.

Kahle H.P., Karjalainen T., Schuck A., Ågren G.I., Kellomäki S., Mellert K.H., Prietzel J., Rehfuess K., Spiecker H. (2008): Causes and Consequences of Forest Growth Trends in Europe – Results of the RECOGNITION Project. European Forest Institute Research Report. Leiden, Brill: 261.

Kallio A.M.I., Houtmeyers S., Aza A. (2023): On carbon substitution and storage factors for harvested wood products in the context of climate change mitigation in the Norwegian forest sector. Environmental and Climate Technologies, 27: 254–270.

Korosuo A., Pilli R., Abad Viñas R., Blujdea V.N.B., Colditz R.R., Fiorese G., Rossi S., Vizzarri M., Grassi G. (2023): The role of forests in the EU climate policy: Are we on the right track? Carbon Balance and Management, 18: 15.

Korpel Š. (1989): Pralesy Slovenska. 1st Ed. Bratislava, Veda: 328. (in Slovak)

Kučera M., Adolt R. (2019): Národní inventarizace lesů v České republice – Výsledky druhého cyklu 2011–2015. Brandýs nad Labem, Ústav pro hospodářskou úpravu lesů Brandýs nad Labem: 440. (in Czech)

Landry G., Thiffault E., Cyr D., Moreau L., Boulanger Y., Dymond C. (2021): Mitigation potential of ecosystem-based forest management under climate change: A case study in the boreal-temperate forest ecotone. Forests, 12: 1667.

Leskinen P., Cardellini G., González-García S., Hurmekoski E., Sathre R., Seppälä J., Smyth C., Stern T., Verkerk P.J. (2018): Substitution Effects of Wood-based Products in Climate Change Mitigation. From Science to Policy 7. Joensuu, European Forest Institute: 28.

Lindroth A., Tranvik L. (2021): Accounting for all territorial emissions and sinks is important for development of climate mitigation policies. Carbon Balance and Management, 16: 10.

Liu Z., Deng Z., Davis S.J., Ciais P. (2024): Global carbon emissions in 2023. Nature Reviews Earth & Environment, 5: 253–254.

Máslo J., Adolt R., Kohn I., Kučera M. (2023): Národní inventarizace lesů – Výsledky třetího cyklu 2016–2020. Brandýs nad Labem, Ústav pro hospodářskou úpravu lesů Brandýs nad Labem: 7. (in Czech)

https://doi.org/10.17221/74/2024-JFS

Mo L., Zohner C.M., Reich P.B., Liang J., De Miguel S., Nabuurs G.J., Renner S.S., Van Den Hoogen J., Herold A.A.M. et al. (2023): Integrated global assessment of the natural forest carbon potential. Nature, 624: 92–101.

Moreau L., Thiffault E., Kurz W.A., Beauregard R. (2023): Under what circumstances can the forest sector contribute to 2050 climate change mitigation targets? A study from forest ecosystems to landfill methane emissions for the province of Quebec, Canada. GCB Bioenergy, 15: 1119–1139.

Pretzsch H., Biber P., Schütze G., Uhl E., Rötzer T. (2014): Forest stand growth dynamics in Central Europe have accelerated since 1870. Nature Communications 5: 4967.

Pretzsch H., Del Río M., Arcangeli C., Bielak K., Dudzinska M., Forrester D.I., Klädtke J., Kohnle U., Ledermann T., Matthews R., Nagel J., Nagel R., Ningre F., Nord-Larsen T., Biber P. (2023): Forest growth in Europe shows diverging large regional trends. Scientific Reports, 13: 15373.

Prietzel J., Falk W., Reger B., Uhl E., Pretzsch H., Zimmermann L. (2020): Half a century of Scots pine forest ecosystem monitoring reveals long-term effects of atmospheric deposition and climate change. Global Change Biology, 26: 5796–5815.

Roe S., Streck C., Beach R., Busch J., Chapman M., Daioglou V., Deppermann A., Doelman J., Emmet-Booth J., Engelmann J., Fricko O., Frischmann C., Funk J., Grassi G., Griscom B., Havlik P., Hanssen S., Humpenöder F., Landholm D., Lomax G., Lehmann J., Mesnildrey L., Nabuurs G., Popp A., Rivard C., Sanderman J., Sohngen B., Smith P., Stehfest E., Woolf D., Lawrence D. (2021): Land-based measures to mitigate climate change: Potential and feasibility by country. Global Change Biology, 27: 6025–6058.

Sathre R., O'Connor J. (2010): Meta-analysis of greenhouse gas displacement factors of wood product substitution. Environmental Science & Policy, 13: 104–114.

Schulze E.D., Stupak I., Hessenmöller D. (2019): The climate mitigation potential of managed versus unmanaged spruce and beech forests in Central Europe. In: Magalhães Pires J.C., Da Cunha Gonçalves A.L. (eds): Bioenergy with Carbon Capture and Storage. Cambridge, Elsevier Academic Press: 131–149.

Simanov V. (1996): Tabulky koeficientů výtěžnosti sortimentů surového dříví. (unpublished; in Czech)

Smyth C., Rampley G., Lemprière T.C., Schwab O., Kurz W.A. (2017): Estimating product and energy substitution benefits in national-scale mitigation analyses for Canada. GCB Bioenergy, 9: 1071–1084.

Thomas S.C., Martin A.R. (2012): Carbon content of tree tissues: A synthesis. Forests, 3: 332–352.

Valade A., Bellassen V., Magand C., Luyssaert S. (2017): Sustaining the sequestration efficiency of the European forest sector. Forest Ecology and Management, 405: 44–55.

Vrška T., Hort L., Adam D., Odehnalová P., Horal D. (2002): Dynamika vývoje pralesovitých rezervací v České republice. Svazek I, Českomoravská vrchovina – Polom, Žákova hora. Prague, Academia: 213. (in Czech)

Vrška T., Adam D., Hort L., Odehnalová P., Horal D., Král K. (2006): Dynamika vývoje pralesovitých rezervací v České republice. Svazek II., Lužní lesy – Cahnov-Soutok, Ranšpurk, Jiřina. Prague, Academia: 214. (in Czech)

Zhang X., Chen J., Dias A.C., Yang H. (2020): Improving carbon stock estimates for in-use harvested wood products by linking production and consumption – A global case study. Environmental Science & Technology, 54: 2565–2574.

Received: September 19, 2024
Accepted: December 19, 2024
Published online: March 25, 2025