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The potential for storing carbon by harvested wood products

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Forest ecosystems are a critical component of the global carbon cycle, which stores carbon in both vegetation biomass and soil organic matter. Timber harvesting can laterally move the carbon stored in forest sectors to harvested wood products (HWPs) and thus create an HWPs carbon pool. The carbon stored in HWPs is allocated to end-use wood products (e.g., paper, furniture), landfills (e.g., waste wood materials), and charcoal (e.g., non-energy use biochar). Environmental change is predicted to have far-reaching effects on the carbon stored in HWPs by altering the timber supply. In addition, technological advancement in the wood industry accelerates the carbon inflow rate by promoting processing efficiency and reduces the outflow rate by creating innovative wood products with a longer service life. Socioeconomic factors such as population and household income also contribute to the carbon stock changes in wood products by expanding or reducing the demand. Given numerous factors that are correlated with the size of HWPs carbon pool, an advanced and comprehensive understanding of these factors on modifying the HWPs carbon storage is essential to modeling and predicting the carbon stored in HWPs, atmospheric CO_2 concentration, and global warming; therefore, we reviewed, summarized, and discussed the function of these factors in regulating the carbon stored in HWPs.

KEYWORDS
carbon storage, environmental change, harvested wood products, prediction, socioeconomic factors, technological advancement

Introduction

Forest ecosystems are a critical component of the global carbon cycle, which sequester atmospheric CO_2 by photosynthesis and release carbon by the total ecosystem respiration as well as wildfires (Wei and Larsen, 2018; Harris et al., 2021; Nolan et al., 2021). Pan et al. (2011) reported that the carbon stock in global forest ecosystems is 861 ± 66 Pg C with a sink rate of 2.4 ± 0.4 Pg C per year, which creates the largest carbon pool in the terrestrial biosphere. Disturbances including wildfire and harvesting can directly remove the carbon from forest ecosystems (Seidl et al., 2014). Global wildfire vertically releases the carbon to the atmosphere through biomass combustion with an average rate of 2.2 Pg C per year (Bowman et al., 2009; Van Der Werf et al., 2017).

In addition, world's timber harvesting laterally moves the carbon from forest ecosystems to HWPs, which has a mean of 1.04 Pg C per year (Brunet-Navarro et al., 2017; Zhang et al., 2020). The regrowth of trees following wildfires and timber harvesting is expected to be an important driver behind the large uptake of atmospheric CO_2 (Pugh et al., 2019). Unlike wildfires, timber harvesting moves the carbon from forest sections to HWPs and creates a HWPs carbon pool, which can store the carbon for a long period and contribute to the mitigation of greenhouse effects (Gustavsson et al., 2006).

As a part of the lateral carbon export from forest ecosystems (Ciais et al., 2008; Wei et al., 2021), timber harvesting initially moves the carbon from forests to primary wood products (e.g., lumber, pulp, and plywood), which are used to make secondary or end-use wood products (e.g., furniture, floor, and building) (Skog and Nicholson, 2000). The carbon flows into the HWPs carbon pool with new wood products, but older wood products will be disposed of when they reach the end of their service lives (**Figure 1**). A part of the disposed wood products is recycled to make new products or reused as biofuel to generate energy, and the remainder is sent to landfills. Therefore, the HWPs carbon pool size can be accounted for by monitoring the carbon inflow and outflow rates (Donlan et al., 2012). In addition, the HWPs carbon pool involves the carbon stored in end-use products (e.g., building, home application, paper, and building), waste wood materials in landfills, and the charcoal (e.g., non-energy use biochar).

To quantify the carbon stored in HWPs, numerous approaches have been developed and they are different in their bulking allocation, industrial processes, carbon pools, and product removal (Brunet-Navarro et al., 2016). Johnston and Radeloff (2019) used historical records together with the IPCC guidance and concluded that the carbon sequestered into global end-use HWPs served as a net sink of 91 Tg C in 2015. In addition, Zhang et al. (2020) found that the carbon sink in global end-use HWPs had an average of 122 Tg C per year during the period of 1992–2015. Across the entire forestry sector and wood products, carbon stored in HWPs is 13% in Australia (Eggers, 2002), 33% in the UK (Dewar and Cannell, 1992), 10% in the USA (Smith and Heath, 2008), and 10% in Europe (Eggers, 2002). Therefore, including the carbon stored in HWPs is required to estimate the land-atmospheric carbon exchange by using the bottom-up approach (stock change approach).

Existing studies suggest that various factors including environmental change, technological advancement in the wood industry, and plenty of socioeconomic factors can affect the size of HWPs carbon pool by regulating the wood products supply and demand as well as the residential time of wood products in the carbon pool; therefore, an advanced and comprehensive review of their influence is essential to modeling and predicting the potential of this carbon storage and atmospheric CO_2 concentrations. In this study, we reviewed and summarized these factors, and discussed the function of these factors on regulating the carbon stored in HWPs carbon pool.

Environmental change

The changing environment such as climate, atmospheric CO_2 concentration, forest disturbances, atmospheric nitrogen and phosphorus depositions can threaten or accelerate the productivity of forest ecosystems and thus affect the size of HWPs carbon pool by altering the timber supply. For example, the higher temperature may restrict photosynthesis and reduce timber yield in tropical forest ecosystems (Smith et al., 2020); however, in boreal forest ecosystems, the warmer temperature favors not only photosynthesis but also extends the growing season, which can promote timber production (Kirilenko and Sedjo, 2007). In water-deficient forest ecosystems, more precipitation bolsters timber production, but the wetter climate restricts photosynthesis and reduces tree growth rate in water-sufficient forest ecosystems (Husen et al., 2017). In addition, increasing concentrations of atmospheric CO_2 are likely to drive modifications in forest ecosystems and boost the rate of tree growth through the carbon fertilization effect (Beedlow et al., 2004). Existing experiments demonstrate that CO_2 fertilization can induce tree growth enhancement (Gea-Izquierdo et al., 2017). It is, however, unknown how this response would interact with other changed climate conditions. Besides the influence on individual tree growth, climate change can alter the entire forest ecosystems such as tree species composition, forest structure, competition among trees and thus reduce or increase merchantable trees (Lines et al., 2010). Therefore, the response of timber production to climate change is varied in different forest ecosystems.

In addition, climate change reduces timber production by introducing frequent wildfires, outbreaks of insects, and extreme events such as storms and hurricanes, which are more important than the direct impact of higher temperature, less precipitation, and elevated CO_2 concentration. Forest fires directly burn trees and release carbon into the atmosphere, which destroy the entire forest ecosystem and threaten timber production (Cary et al., 2021). Insect outbreaks increase the forest defoliation and tree mortality rate, which reduces the rate of tree growth and substantially decreases timber yield (Chen et al., 2019). Storms and hurricanes can directly destroy trees and result in less timber production (Sun, 2016). In addition, they cause a lower rate of tree growth by reducing the available soil nutrients and changing the soil texture (Sun et al., 2022); therefore, the reduction of timber production continues for several years.

The supply of nitrogen limits the timber production in most boreal and temperate forest ecosystems (Högberg et al., 2017); therefore, more nitrogen deposition accelerates the tree growth and provides more timber yield. Tropical forests are commonly on the old and highly weathered soils, which

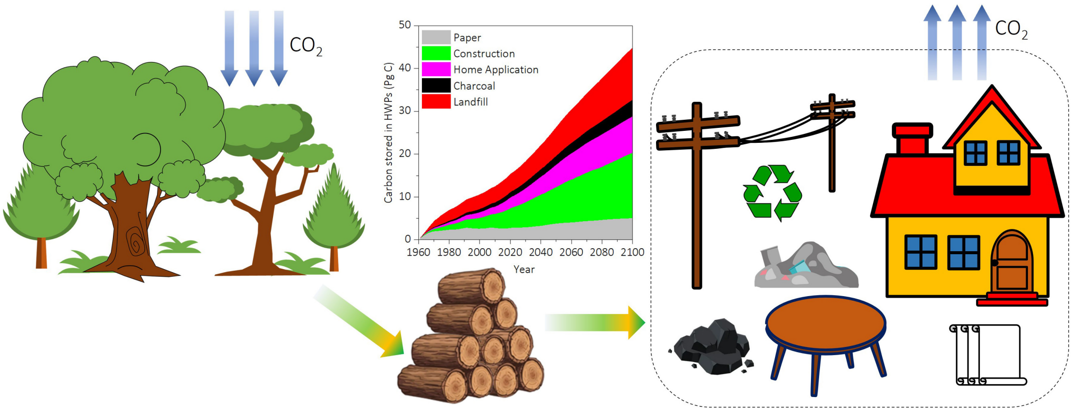

FIGURE 1
The carbon flux from forest sectors to the harvested wood products (HWPs) carbon pool and the predicted carbon accumulated in the global HWPs carbon pool from 1961 to 2100 (The carbon accumulated in HWPs carbon pool from 1961 to 2100 was estimated with the data and accounting framework provided by Daigneault et al. (2022) and Li et al. (2022), respectively).

have been experiencing a long-term phosphorus depletion and ultimately enter a phase of phosphorus limitation (Turner et al., 2018). Thus, additional supply of phosphorus from atmospheric deposition can enhance forest productivity.

Technological advancement

Technological improvement in the wood industry can promote the utilization of low-quality and small diameter logs, advance the wood products processing efficiency, develop innovative wood products with longer service life, and increase the recycling rate, which potentially expands the size of HWPs carbon pool (Li et al., 2022). For instance, the technological advancement in the wood industry has promoted the lumber yield as much as 70% for logs with small-end diameter (Shmulsky and Jones, 2019). In addition, with the invention and prevalent use of wood composite products, sawmills distribute their processing residues to the downstream wood product manufacturers, leaving nearly zero waste (Bowyer et al., 2012). Other than burning to generate energy, using small-diameter trees and processing residues to produce lumber and wood composite products can store the carbon for a longer period.

Innovative wood products, such as mass timber panel and rigid low-density wood fiber insulation panels, have been widely used in building systems to substitute for high embodied carbon materials of steel, concrete, brick, and petroleum-based insulation, which can expand the application of timber and reduce the embodied carbon (Cetiner and Shea, 2018; Cabeza et al., 2021). Meanwhile, these innovative wood products can stimulate the harvesting of mass timber favorite tree species and exploit the market of wood products. Although traditional wood building materials such as dimension lumber and oriented strand board still dominate the residential housing market, mass timber buildings are becoming more and more popular in mid-rise and high-rise building systems (Pierobon et al., 2019). Ganguly et al. (2017) reported that the cumulative demand for Cross-Laminated Timber (CLT) panels in the Pacific Northwest is estimated to be 56 million cubic feet between 2016 and 2035. The global market for CLT exceeded $660 million in 2018 and the annual demand is projected to grow by over 13% into the mid-2020s (IMARC Group, 2022). This high demand expands the carbon stored in HWPs.

Compared to traditional wood materials, these innovative products used in buildings and home applications can store carbon for a longer period. In addition, advanced wood processing technology such as pressure- and thermal- treated lumber can extend the service life of wood products for exterior use up to 50 years (Brischke et al., 2006). Because pressure- and thermal- treated lumber are widely used in decking and the global wood decking market has a size of more than $15 billion (Global Market Insights Research [GMIRR], 2022), it can store substantial amounts of carbon and contribute to the mitigation of the greenhouse effect. Since the 2000s, non-energy use biochar has become a popular bioproduct to amend the soil in agricultural land (Lal et al., 2001). Currently, the annual non-energy use biochar production is small; however, due to the resistant property biochar can be accumulated to a relatively significant stock (Wei et al., 2018). Currently, the biochar market is mainly in North America and Europe, taking approximately 70% of the global market. The global biochar market is $2 billion and predicted to have an annual increasing rate of over 10% (Prescient and Strategic Intel Market Research Reports [PSI-MRR], 2022). This increasing demand of biochar will create a substantial long-term carbon sink.

Recyclable wood products, including paper products, wood building materials, and wood pallets, can be used to reproduce new products, which minimizes the waste wood materials that are sent to landfills and extends the residential time of carbon in end-use wood products (Mallo and Espinoza, 2015). Technological improvement greatly increases the percentage of recyclable waste wood materials. For example, in the United States, the Environmental Protection Agency (EPA) reported that 1% of the waste solid wood materials was recycled to make new products, and this rate was increased to 17% in 2018. In addition, the EPA reported that 17% of the paper and paperboard were made by recycled wood materials in the United States in the 1960s, and this fraction was increased to 68% in 2018.

Socioeconomic factors

The rapid development of the global economy in parallel with the boom of the population over the past four decades accelerates the demand of wood products including furniture, constructions, and paper products, which has substantially expanded the size of HWPs carbon pool (Zhang et al., 2020; Zhao et al., 2022). Residential construction has been boosted to meet the increasing housing demand for the growing population, meanwhile, the demand of wood products for home decor has been steadily growing along with the rising residential space (Zhao et al., 2020). Urbanization is another critical factor that positively correlated with the demand of wood products (Zhao et al., 2013). Urbanization rate is increasing globally, 10% of the population lived in urban areas in 1900, and it was increased to 57% in 2021 (World Bank, 2022). According to the estimation reported by the United Nations, 66% of the world's population will reside in the urban area by 2050 (United Nations Department of Economic and Social Affairs [DESA UN], 2014), and this percentage will be increased to 85% by the end of the twenty-first century (OECD, 2015). Thus, with the urbanization process, we will see a rise in wood products used for home applications and constructions. Mishra et al. (2022) found that if 90% of the new urban people build their houses with wooden materials, 106 Pg of CO_2 will be sequestered by 2100.

Skjerstad et al. (2021) suggested that the sawn wood consumption will continue increasing in line with the future economic growth. Besides, a higher household income is typically associated with high demand for timber products especially those used in constructing buildings and making furniture. Brack (2018) found that the quality of consumed wood products is positively correlated with the household income, which reduces the carbon outflow rate by extending the residential time of wood products. Besides, the rising household income can change the consumers' preference and they will purchase more eco-friendly or sustainable products, which is a guarantee of the high demand for durable wood products. Although paper products, such as packaging or graphical paper are generally of shorter service life, the high demand for paper products can form a large quick-turnover carbon pool and store substantial carbon (Skog and Nicholson, 2000). Therefore, incorporating these socioeconomic influences is essential to predicting the potential carbon storage in HWPs.

Discussion

Besides environmental change, technological improvement in the wood industry, and socioeconomic changes, forest management strategies also contribute to the carbon storage in HWPs. Climate change is expected to increase forest vulnerability through extreme weather and severe disturbances; however, forest managers are therefore investigating management strategies to increase forest resistance and resilience including promoting the complexity of forest structure and reducing the proportion of large trees (Barreto et al., 1998; Birdsey et al., 2006; Diao et al., 2022). For example, silvicultural strategies such as weed suppression, initial spacing, respacing before canopy closure, thinning after canopy closure, and rotation length are efficient approaches to control the timber yield (Macdonald and Hubert, 2002). Fertilization is also a useful way to promote the tree growth rate, especially by fertilizing more nitrogen and phosphorus (Routa et al., 2011). Soil amendment with biochar is another important approach to accelerate timber yield by improving soil porosity, decreasing tensile strength, and increasing soil pH (Knowles et al., 2011). In addition, genetic improvement advances timber quality and increases timber yield by promoting the growth rate and forest resistance to the disease, insect, as well as extreme weather (Ahtikoski et al., 2018; Mckenna and Coggeshall, 2018).

Policy is a critical factor that regulates the carbon stored in the HWPs carbon pool, which can promote timber production, facilitate the development of wood industry, and increase the demand (Moiseyev et al., 2010). For example, in 2022, the Inflation Reduction Act in the United States was announced and allocated $30 billion through U.S. Forest Service for nature-based climate solutions, which can provide incentives to protect forested land and adopt climate-smart forestry practices. Because HWPs can offset carbon emissions, policies related to the carbon credit market can make the carbon sequestration in wood products traded in voluntary or regulatory carbon markets (Blanc et al., 2019). Biomass fuel, especially wood pellets, is a renewable energy, policies related to enhancing sustainable development can expand and regulate the use of biomass fuel, such as tax credits for biomass facilities and subsidy for the power purchase agreements (Lynd, 1996). In the United States, the Energy Policy Act (2005) and the Energy Independence and Security Act (2007) provides incentives for the wide use of biomass fuel. Moreover, the Inflation Reduction Act provides a 30% tax credit for those who use efficient pellet stoves or larger residential biomass heating systems. Similar regulations have been enacted around the world such as Sweden, Finland, and Austria (Howard et al., 2021). These policies can greatly promote the demand for wood products. The decomposition of waste wood materials in landfills has been recognized as a significant methane emission (Pingoud and Wagner, 2006); therefore, policy approaches such as promoting the recycling rate of waste wood materials have been applied in the United States to reduce the methane emission and combat climate change (Powell et al., 2016).

Given that plenty of factors are correlated with the carbon stored in the HWPs carbon pool by modifying the carbon inflow, residential time, and the outflow rate, it is a challenge to predict the size of HWPs carbon pool. Johnston and Radeloff (2019) used plausible futures of wood products outlined by the shared socioeconomic pathways to predict the world's carbon storage in end-use HWPs and concluded that the total storage will be accumulated to as much as 2 Pg C by 2065. While this prediction is highly dependent on the economic development and the timber production is not well represented in their estimates. We incorporated the global consumption of wood products predicted by Daigneault et al. (2022) together with the HWPs carbon storage accounting framework developed by Li et al. (2022) to roughly estimate the carbon accumulated in HWPs carbon pool from 1961 to 2100 and concluded a storage of 48 Pg C by 2100 (**Figure 1**). Assuming there is no change of the carbon stock in global forest ecosystems, the size of HWPs carbon pool is 5.5% of the carbon stored in the entire forestry sector and wood products. However, the prediction performed by Daigneault et al. (2022) excludes the environmental change on timber supply and the influence caused by technological improvement. To model and predict timber production, the earth system model is a powerful approach to predict the merchantable trees, which can incorporate climate change, forest structure change, and available nutrients (Koven et al., 2020).

As an important carbon pool, wood products contribute to the mitigation of greenhouse gas effects, and it should be considered when using the bottom-up approach to estimate the land-atmospheric carbon exchange. The HWPs carbon pool can be regulated by various factors; therefore, it is a challenge to incorporate all these factors in a prediction. To accurately predict the carbon storage in HWPs, it is necessary to conduct an analysis and identify key factors that strongly correlate with the target HWPs carbon pool.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work, and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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