Global mitigation potential of carbon stored in harvested wood products

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Carbon stored in harvested wood products (HWPs) can affect national greenhouse gas (GHG) inventories, in which the production and end use of HWPs play a key role. The Intergovernmental Panel on Climate Change (IPCC) provides guidance on HWP carbon accounting, which is sensitive to future developments of socioeconomic factors including population, income, and trade. We estimated the carbon stored within HWPs from 1961 to 2065 for 180 countries following IPCC carbon-accounting guidelines, consistent with Food and Agriculture Organization of the United Nations (FAOSTAT) historical data and plausible futures outlined by the shared socioeconomic pathways. We found that the global HWP pool was a net annual sink of 335 Mt of CO_2 equivalent $(CO_2e)\cdot y^{-1}$ in 2015, offsetting substantial amounts of industrial processes within some countries, and as much as 441 Mt of $CO_2e\cdot y^{-1}$ by 2030 under certain socioeconomic developments. Furthermore, there is a considerable sequestration gap (71 Mt of $CO_2e\cdot y^{-1}$ of unaccounted carbon storage in 2015 and 120 Mt of $CO_2e\cdot y^{-1}$ by 2065) under current IPCC *Good Practice Guidance*, as traded feedstock is ineligible for national GHG inventories. However, even under favorable socioeconomic conditions, and when accounting for the sequestration gap, carbon stored annually in HWPs is <1% of global emissions. Furthermore, economic shocks can turn the HWP pool into a carbon source either long-term—e.g., the collapse of the USSR—or short-term—e.g., the US economic recession of 2008/09. In conclusion, carbon stored within end-use HWPs varies widely across countries and depends on evolving market forces.

carbon sequestration | harvested wood products | climate change | forest sector | shared socioeconomic pathways

Carbon stored in harvest wood products (HWPs) can have multiple effects on national greenhouse gas (GHG) inventories, where HWPs in end use play a key role. However, the global potential of HWPs as a carbon sink is both unknown and difficult to assess. In 2015, a total of 197 countries ratified the Paris Agreement, encouraging parties to "conserve and enhance, as appropriate, sinks and reservoirs of greenhouse gases. . .including forests" (ref. 1; art. 4.1d), allowing countries to account for the carbon stored within forests, and addresses activities that have forest carbon benefits after forests are harvested, including carbon stored in HWPs. However, depending on the balance between carbon inflows and outflows, the HWP pool can be either a carbon sink or source, as carbon is added to the HWP pool when new products are produced and released when older products reach the end of their useful life and are burned, potentially offsetting fossil emissions, or sent to solid-waste disposal sites (SWDSs), where they decompose to varying rates. Ultimately, socioeconomic factors, including population, income, and trade, will determine the amount of wood products produced and consumed in the future, and, thus, the carbon sequestration potential of the HWP pool on regional and global scales. Income levels are expected to rise (2), as is population, at least until 2050 (3). However, beyond that, the future developments of socioeconomic factors are uncertain, making the contribution of HWP production to carbon stored within HWPs in end uses difficult to predict.

The consideration of HWPs as a carbon-storage mechanism is relatively new. The Intergovernmental Panel on Climate Change (IPCC) first recognized HWPs in their *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (4), but expressed a default assumption that "all carbon biomass harvested is oxidized in the removal [harvest] year" (*Land Use Change and Forestry*, 5.17, box 5), and this approach was adopted during the first Kyoto Protocol commitment period (2008–2012). Then, in their *2006 Guidelines* (5), the IPCC revised their treatment of HWPs, proposed accounting guidelines, and allowed Annex I parties to account for carbon benefits. In 2011, at the 17th Conference of Parties (COP17), members concluded that only HWPs made from domestic harvests can contribute toward national GHG inventories, implying the production approach as the new standard moving forward. The IPCC subsequently published the *2013 Revised Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol* (6), adding HWPs as a mandatory pool to be reported within land use, land use change, and forestry (LULUCF) activities, and updated the reporting methods for the production approach to be employed by Annex I parties during the second Kyoto period. Moving forward, countries are preparing to report their HWP carbon pool within their Nationally Determined Contributions under the Paris Agreement. Given this relatively new focus on HWPs, the question is what their global mitigation potential may be.

Prior work (see ref. 7 for a review) has focused on the carbon budget (8, 9) or methods for accounting for carbon in HWPs (8, 10, 11). In recent years, country-level analyses have been conducted on historical data, finding an increase in the accumulation of carbon within the HWP pool in the United States (11), Portugal (12), Canada (13), Ireland (14), the European Union (15), Japan (16), and China (17). Others have shown similar historic trends across the globe (8, 10), but relied on outdated

Significance

Carbon stored within harvested wood products (HWPs) may be a tool to mitigate climate change, yet its global potential as a carbon sink is unknown and difficult to assess. We show that the global HWP pool was a net sink of 335 Mt of CO_2 equivalent $(CO_2e)\cdot y^{-1}$ in 2015 and as much as 441 Mt of $CO_2e\cdot y^{-1}$ by 2030, offsetting substantial amounts of industrial process emissions, but only in some countries, and the global contribution is minor, even in a scenario of favorable conditions. Furthermore, economic shocks can turn a country's HWP pool into a net source of carbon. In conclusion, carbon stored within end-use HWPs varies widely across countries and depends on evolving market forces.

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accounting methods. Meanwhile, few have projected future carbon emissions and removals in the HWP pool, and those that have focused on regional- or national-level estimates and employed ad hoc future scenarios that have little economic support behind the evolution of wood product markets (13, 15, 16). Consequently, the future potential of the harvested wood carbon pool is poorly understood, even though it is now mandatorily included within current IPCC *Good Practice Guidance*.

Indeed, changes in carbon stocks associated with the production and end use of HWPs fall within a broader system (*SI Appendix, Forest Sector System Boundary*), which includes forest ecosystem carbon balance, attendant changes in manufacturing emissions from displaced products (e.g., concrete, steel, and fossil fuel), emissions from biofuels, and decay in SWDSs. While the literature has examined carbon pools associated with different components within this boundary (7), our primary focus here is on end-use HWPs.

We provide here a comprehensive global estimate of the contribution of HWP to carbon stored in HWPs in end uses based on disaggregated country-level data and future predictions driven by country-specific variability in socioeconomic factors across time. We primarily relied on open-access data from the Food and Agriculture Organization of the United Nations (FAOSTAT; ref. 18), which provides country-level data on the production, import, and export of forest products, beginning in 1961. To predict future trends in global forest product markets, we paired a publicly available economic model of wood markets that is calibrated to FAOSTAT data (*SI Appendix, Global Forest Products Model*) to five shared socioeconomic pathways (SSPs) that describe a series of different futures surrounding plausible demographic, economic, technological, social, governance, and environmental factors (19–21). The development of international wood markets will play a critical role in the magnitude of the HWP carbon pool within national GHG inventories.

We show that the HWP sink is growing globally, but the magnitude of the contribution estimates of HWPs differs among future socioeconomic pathways. We also find that the current 2013 IPCC *Good Practice Guidance* underestimates the contribution of the HWP carbon stored in end uses because it only includes products produced from domestic harvests in national GHG inventories and ignores traded timber. However, even under a best-case scenario, and when accounting for this gap, the global potential of HWPs as a carbon sink is minor and always <1% of emissions. Furthermore, analyzing historical data at the country level shows that economic shocks can play a major role in the carbon emissions or removals in a country's HWP pool.

Production of Wood Products. Global harvest and the production of wood products has risen markedly over the historical period from 1961 to 2015 (Fig. 1 *A* and *B*), according to FAOSTAT data. Our projections show that those increases will generally continue from 2015 to 2065 for all five SSPs, albeit at varying rates (*SI Appendix*, Tables S8–S13). Specifically, global harvests have risen from 2.1 billion m^3 in 1961 to 3.78 billion m^3 in 2015 (Fig. 1*A*), and we project them to reach 4.2 billion m^3 by 2065 under SSP5 due to rapid economic growth. Alternatively, if the future sees increasing disparities in economic growth as described under SSP4, global harvests could be relatively stagnant over the next 50 y. The "business-as-usual" SSP2 scenario (with minimal changes in historical socioeconomic conditions) leads to a modest rise in global harvests from 2015 to 2030 of 100 million m^3 and remains stagnant through 2065. Similar trends are projected for the global market for wood-processing inputs like industrial roundwood and wood pulp (Fig. 1*A* and *SI Appendix*, Tables S8 and S9), as future harvests are ultimately driven by the

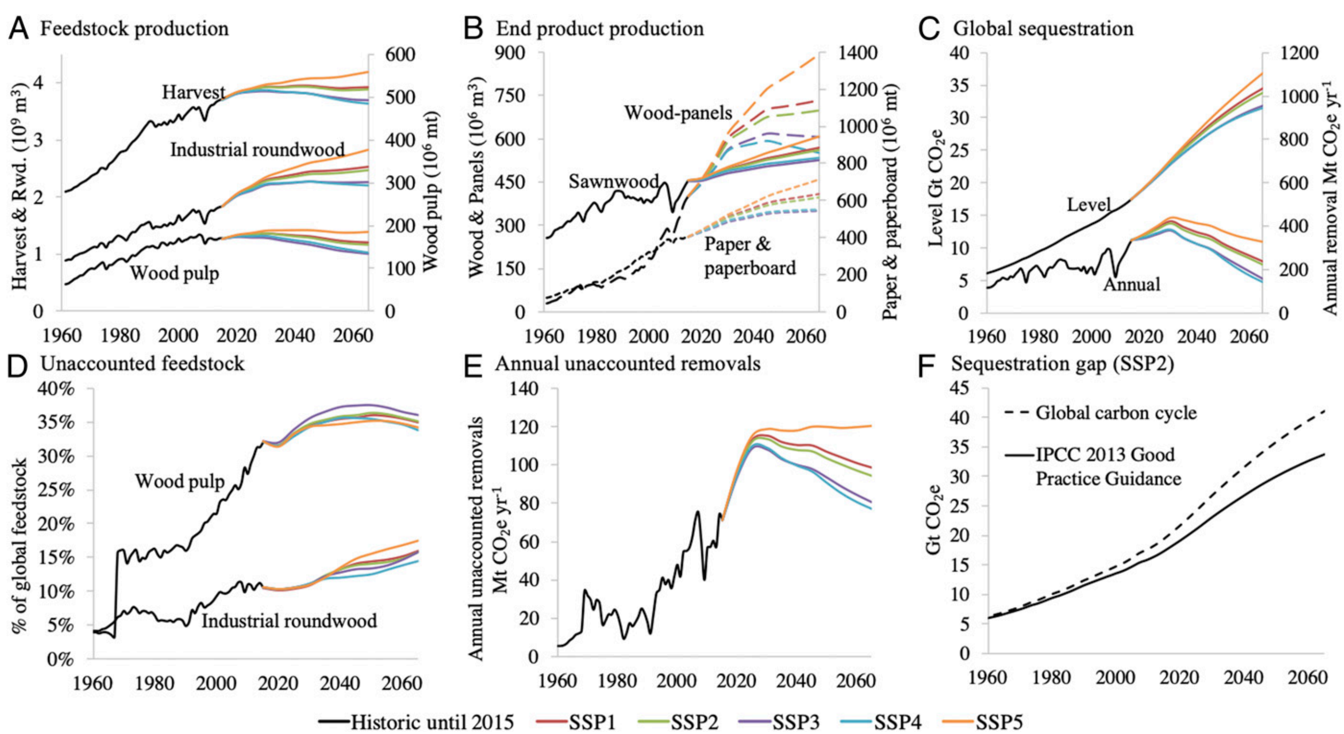

Fig. 1. Projected global HWP market and carbon-pool data for 1961–2015 from FAOSTAT, projections for 2016–2065 from the GFPM for SSP1–5. (*A*–*C*) Global production of feedstock (*A*) and end-product groupings (*B*) drive the total level of carbon stored within HWPs and the net annual carbon flux (year-to-year change) in the HWP pool (*C*). (*D* and *E*) Current IPCC accounting methods ignore carbon stored in products manufactured from foreign feedstock, with *D* displaying the proportion of unaccounted feedstock, leading to an amount of unaccounted removals each year (*E*). (*F*) Consequently, a gap exists between the actual global carbon cycle of HWPs and those inventoried under IPCC *2013 Good Practice Guidance*. Global estimates are based on disaggregated country and commodity information.

demand for downstream products such as sawnwood, wood-based panels, and pulp and paper.

Global sawnwood production also has risen strongly: Consumption in 1961 was 231 million m^3, rising to 454 million m^3 by 2015 (Fig. 1*B* and *SI Appendix*, Table S10). Our projections suggest that this trend will continue across all SSPs, but the rise is most rapid under SSP5, where sawnwood production is projected to rise to 606 million m^3 by 2065. Under the business-as-usual SSP2 scenario, we project a production of 560 million m^3 by 2065, but under SSP3, we project a more modest rise to 526 million m^3 due to slower economic development.

The global pattern of wood-panel production experienced exponential growth in the past two decades, but we project this rate to start slowing in ~2040 (Fig. 1*B* and *SI Appendix*, Table S11). Still, production has expanded from 25 million m^3 in 1961 to 402 million m^3 in 2015, and, by 2065, we project production to be between 605 million and 894 million m^3. The most substantial growth is seen under SSP5, and less so under SSP4. Under the business-as-usual SSP2 scenario, we project production to rise to 700 million m^3 by 2065. Production is projected to continue to grow until 2065 under SSP1, SSP2, and SSP5, while global production will plateau by 2040 under SSP3, and even sooner under SSP4.

The global pattern of paper and paperboard production has risen steadily from 1961 to 2015, from 88 million to 407 million m^3 (Fig. 1*B* and *SI Appendix*, Table S12). We project this increase to continue by as much as 306 million m^3 over the next 50 y under SSP5, or as little as 139 million m^3 under SSP3. The business-as-usual SSP2 scenario projects that consumption of paper and paperboard will rise to 615 million m^3 in 2065. The continued rise in this category is the result of packaging-material production growing faster than printing- and writing-paper markets are contracting.

Carbon Flux in HWPs. Carbon in the global HWP pool has increased concomitantly with the increase in past production levels, and projections from 2015 to 2065 show similar trends, but with variation across socioeconomic futures (Fig. 1*C*). We project the amount of carbon stored within HWPs to continue to rise until 2065 across all plausible futures, but the rate of growth to slowly decline as future production rates are insufficient to compensate for the decay of inherited emissions from past production. Consequently, the net annual removals by this pool are estimated to peak in ~2030 between 317 and 415 Mt of CO_2 equivalent $(CO_2e)\cdot y^{-1}$, based on future socioeconomic conditions (Fig. 1*C*).

The scenario that yields the highest annual rate of sequestration in 2065 according to our projections is SSP5, with a net removal of 328 Mt of $CO_2e\cdot y^{-1}$ (Fig. 1*C*). Here, gross domestic product (GDP) per capita is assumed to increase rapidly, and free trade results in a high level of wood-product consumption. Alternatively, SSP4 yields the lowest annual sequestration of 142 Mt of $CO_2e\cdot y^{-1}$ by 2065, as increasing economic disparities persist, and access to markets is limited in poor countries, reducing overall production levels. The mitigation potential under the business-as-usual SSP2 scenario leads to a more moderate annual rate of sequestration of 220 Mt of $CO_2e\cdot y^{-1}$ by 2065.

Annual contribution estimates are projected to vary substantially, both within and across SSPs. The SD in the average annual rate of global sequestration from 2015 to 2065 is estimated to be $\pm$13 Mt of $CO_2e\cdot y^{-1}$ across SSPs. However, there is greater variation for annual contribution estimates across time within a given SSP. Estimates for SSP5 fall between 328 and 441 $\pm$ 40 Mt of $CO_2e\cdot y^{-1}$ during 2015–2065 due to high economic growth, where a world described by increasing inequalities under SSP4 leads to annual contribution estimates between 142 and 383 $\pm$ 82 Mt of $CO_2e\cdot y^{-1}$ during this time. This highlights the need to have HWP carbon removals occur at a rate that is sufficient to offset inherited emissions from historic production levels, and, if the storage and emissions in SWDSs are included in an evaluation, the removals would need to exceed the CO_2e of CO_2 and CH_4 emissions from those sites.

In addition to global variation in the HWP carbon pool, we found strong variation at the country level (Fig. 2 and *SI Appendix*, Table S13). We estimate that the highest annual net carbon removals occur in timber-producing countries, such as China, Canada, the United States, and Russia, and to a lesser degree in South American countries, such as Brazil, and Scandinavian countries, such as Sweden. Canada was a net sink of emissions in 2015, but projections to 2065 indicate that reduced production of sawnwood and a shrinking pulp and paper industry will make removals insufficient to offset inherited emissions from historically high levels of production in these sectors. A similar situation occurs in other countries for which we project a net release of carbon from the HWP pool in the future under certain SSPs, including Japan and Australia, some African countries (e.g., Uganda and Nigeria), and some Eastern European countries (e.g., Bulgaria and Croatia).

Accounting and Sequestration Gap. According to the 2013 IPCC *Good Practice Guidance* accounting, only wood products produced (including exported end products) from domestically sourced inputs contribute to national GHG inventories, and exporting nations cannot claim carbon stored in foreign end products. Consequently, a sequestration gap is created between what is actually stored in HWPs and what is reported in national GHG inventories following IPCC *Good Practice Guidance*. In 2015, 10.5% of global industrial roundwood was traded and unaccounted for, and 32% for wood pulp (Fig. 1*D*). These trends are projected to continue into the future at varying rates, with as much as 38% of global wood pulp production and 18% of industrial roundwood production traded and, therefore, unaccounted for in GHG inventories (for country-level data, see *SI Appendix*, Fig. S2).

Following IPCC *Good Practice Guidance*, there is a significant amount of noninventoried carbon stored in HWPs. In 2015, we estimated that 71 Mt of $CO_2e\cdot y^{-1}$ of net carbon sequestered went unaccounted for, and this could grow to as much as 120 Mt of $CO_2e\cdot y^{-1}$ by 2065 under SSP5 (Fig. 1*E*). The sequestration gap will increase with trade and is predicted to be greatest under SSP5. Every additional year of unaccounted carbon sequestered results in a further divergence of the actual HWPs global carbon cycle from that calculated by using IPCC *Good Practice Guidance*. This gap is estimated to reach 4.8 Gt of CO_2e by 2030 and as much as 7.3 Gt of CO_2e by 2065 under the business-as-usual SSP2 scenario (Fig. 1*F*).

As international climate agreements move toward mandatory accounting for HWP carbon flux, it is important to assess its relative importance by comparing it against other IPCC emissions categories. The global annual carbon stored in the HWP pool represents <1% of total GHG emissions (without LULUCF), but is quite considerable for some countries (Fig. 3). In Canada, for example, HWPs could offset an estimated 2.4% of total GHG emissions (without LULUCF) and nearly 34% of national industrial-process emissions in 2015. Similarly, Sweden's HWP pool could offset an estimated 12% of energy emissions, 72% of industrial process emissions, and almost 9% of total emissions (without LULUCF). However, for the vast majority of countries, the HWP pool represents a small proportion of emissions of other major sectors. The United States, for example, could only offset 0.3% of emissions in the energy sector and 4.6% of industrial-process emissions in 2015. The importance of the contribution of HWP to carbon stored in end uses is small in most countries, but for those where it is large, a broader assessment of the effects of HWPs on emissions and carbon storage would be most important (for country-level data, see *SI Appendix*, Table S15).

Effects of Economic Shocks. An additional challenge for countries that plan to rely on their HWP carbon pool to meet their international climate targets has to do with the effects of unforeseen economic shocks. The potential of HWPs as a carbon

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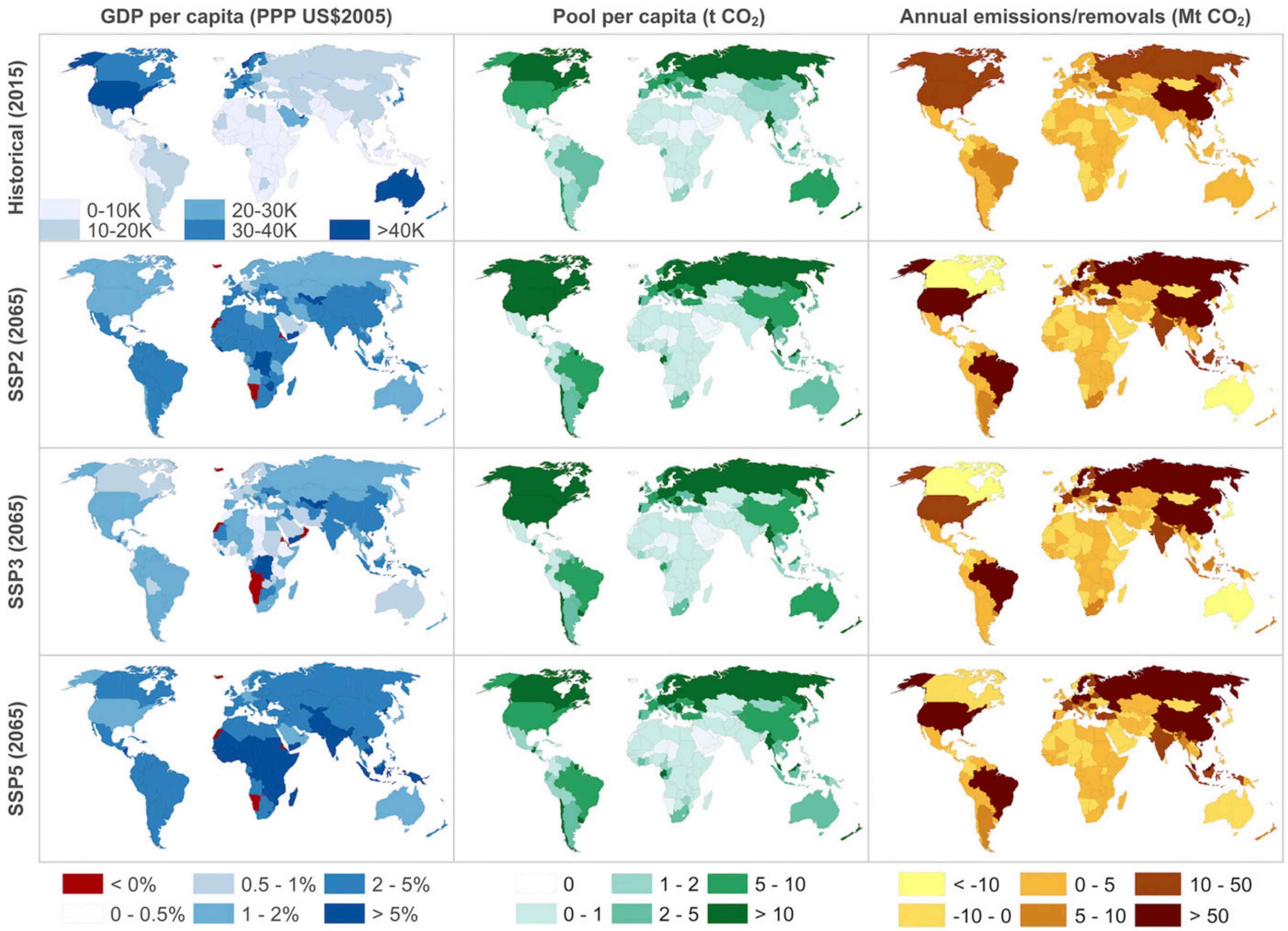

Fig. 2. Spatial patterns in socioeconomic and carbon-pool information for 2015 and projections for 2065. *Left* shows income per capita, first for 2015 measured in GDP/capita purchasing power parity US$2005 dollars, and then in annual average growth rate from 2015 to 2065 for SSP2, SSP3, and SSP5. *Center* depicts the relative magnitude of the carbon pool in each country in terms of tCO_2 per capita in 2015 and in 2065 for SSP2, SSP3, and SSP5. *Right* depicts the annual carbon flux in each country in 2015 and in 2065 for SSP2, SSP3, and SSP5.

sink is only realized if future market activity is sufficient to, at the very least, offset the decay from previously consumed products (15, 22). However, historical examples show that economic shocks lead to major changes in a country's HWP carbon flux.

We consider first the 2008/09 economic recession and its impact on the HWP carbon pool of the United States. From 2007 to 2009, the US consumption of sawnwood fell by 42%, plywood consumption by 32%, and paper consumption by 18%, and, consequently, harvests in the United States fell from 425 million m^3 in 2007 to 332 million m^3 in 2009. The implications on the annual removals of carbon in the HWP pool were substantial, causing a sharp drop in annual carbon sequestration in the HWP pool, resulting in a net source of emissions (Fig. 4*A*). However, since then, the US economy has rebounded sufficiently to continue a trend of net annual removals.

An even more extreme example where historic production rates are no longer met is Russia, due to the collapse of the USSR

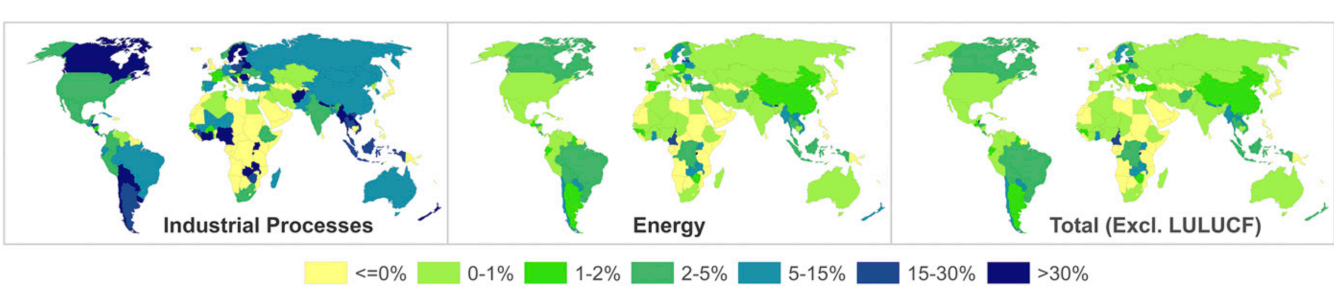

Fig. 3. Spatial patterns in degree with which the domestic HWP pool could offset select IPCC emissions sectors. Calculated as the ratio in the annual carbon flux in the HWP pool to the reported United Nations Framework Convention on Climate Change. GHG data for a given sector. 2015 data were used for all Annex I countries. For non-Annex I countries, the most recent available year's GHG emissions data were used and matched to the annual carbon flux in the HWP pool in that same year. See *SI Appendix*, Table S15 for specific data and years used. Excl., excluding.

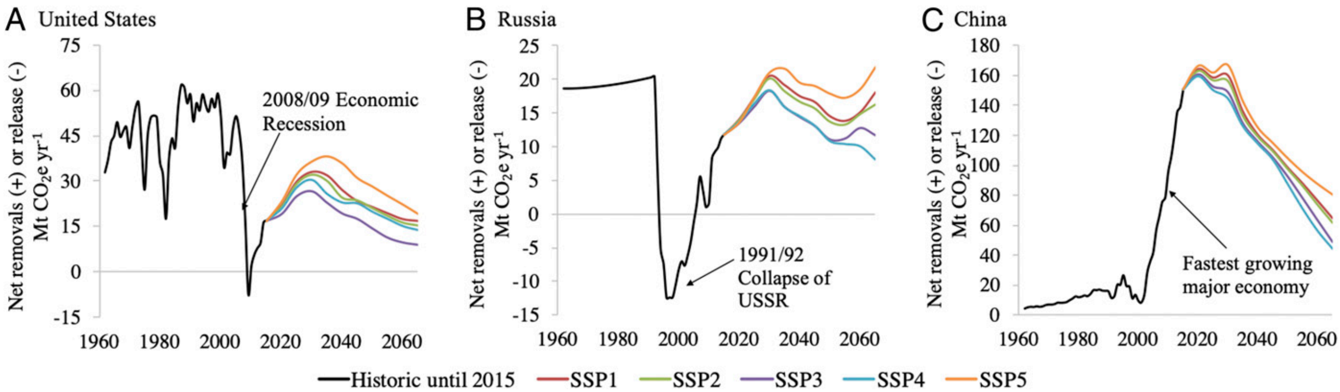

Fig. 4. The effects of economic shocks on the HWP carbon flux in the United States (*A*), Russia (*B*), and China (*C*): For 1961–2015 from FAOSTAT; projections for 2016–2065 from the GFPM for SSP1–5. The development of socioeconomic factors helps determine production levels whereby carbon is added to the HWP pools when new products are produced. Net release of emissions occurs when current production is unable to offset carbon release from previously consumed products as they decay.

in 1991 and its attendant effect on the carbon flux of Russia's HWP pool (Fig. 4*B*). Here, the Russian economy shrank by nearly 30%, followed by years of negative or no economic growth. Consumption of sawnwood in Russia fell from 47 million m^3 in 1991 to 15 million m^3 in 1997, with similar trends for other wood products. Consequently, Russia transitioned from a net sink of carbon in their HWP pool of 21 million Mt of $CO_2e \cdot y^{-1}$ in 1991 to a net source of 13 Mt of $CO_2e \cdot y^{-1}$ in 1995. Unlike the rapid recovery of the US economy after 2008/09, Russia continued to be plagued by the momentum of wood-product decay for the subsequent decades.

Lastly, the rapid accumulation of carbon in the HWPs pool builds momentum for high levels of future decay. A great example is the recent growth in China, where between 2005 and 2015, the consumption of sawnwood rose by an average annual rate of 14%, 11% for plywood, and 5% for paper, which resulted in an exponential accumulation of carbon in HWPs. However, as China's economic growth rate is projected to ease into the future, the transfer of HWPs after use for burning or to SWDSs for storage or decay where the HWP came from the rapid-growth period will outweigh the additions to the pool from future production, leading to a downward trend in future annual net sequestration in the HWP pool (Fig. 4*C*). That is, China must sustain a high level of wood production to ensure that their HWP pool does not become a net source of carbon emissions due to decay.

Conclusion

We estimated the contribution of HWP production and storing carbon in end uses from 1961 to 2065 for 180 individual countries following the IPCC carbon-accounting guidelines, based on FAOSTAT historical data and on plausible futures outlined by the SSPs. Our results suggest that the global HWP pool sequestered 335 Mt of $CO_2e \cdot y^{-1}$ in 2015 and could sequester as much as 441 Mt of $CO_2e \cdot y^{-1}$ by 2030 under favorable socioeconomic conditions, plus an additional 120 Mt of $CO_2e \cdot y^{-1}$ by 2065 due to traded timber that is not accounted for under current IPPC accounting guidelines. Based on our results, the magnitude of carbon storage in HWPs can help to offset a substantial amount of industry process emissions, but only in some timber-producing countries.

Global climate-change agreements are moving toward more reliance on forestry to reduce atmospheric CO_2 levels, including consideration of HWP carbon benefits, but caution should be exercised when integrating their carbon flux because the carbon-sink potential of HWPs is quite sensitive to future socioeconomic conditions. Economic shocks can cause a country's HWP pool to transition from a net sink to a source, with varying degrees of persistence, as seen in Russia and in the United States. The degree to which current climate agreements are willing to accommodate for unforeseen economic shocks remains unknown. China, for example, is accumulating a significant amount of carbon in their HWP pool, which could prove to be a liability if current levels of production and consumption decline.

Indeed, this issue, and our HWP contribution estimates as a whole, could change if life expectancy of HWPs improves into the future. Furthermore, additional mitigation potential may be achieved when substituting emissions-intensive materials (e.g., concrete, steel, and fossil fuels) for HWPs. Ultimately, while we apply the IPCC default approach to input data, more detailed country-level analysis may thus alter the estimates provided here.

In summary, the importance of the contribution of HWPs to carbon storage in end uses is small in many countries, but large in others, and for these countries, a broader assessment of the effects on emissions and carbon storage will be most important to estimate global carbon sink potential (for country-level data, see *SI Appendix*, Table S15).

Materials and Methods

Our analysis consists of two major parts: projections of future wood markets based on an economic model, including an assessment of the implications of future socioeconomic conditions on wood product markets; and the attendant carbon flux within the HWP pool according to IPCC *Good Practice Guidance* accounting methods. We discuss both parts briefly here. Details are provided in *SI Appendix*.

Global Forest-Products Model and Plausible Futures. To predict future trends in global forest-product markets, we employed the Global Forest Products Model (GFPM), which tracks 14 commodity groupings (*SI Appendix*, Table S1) across 180 individual countries (*SI Appendix*, Table S2) and has been the main tool in recent global forest-sector outlook studies published by the US Forest Service (23) and FAOSTAT (24).

The GFPM was calibrated to closely replicate the most recent data reported by FAOSTAT. The GFPM simulates the evolution of the global forest sector by calculating successive yearly market equilibriums by maximizing a quasi-welfare function, as given by the sum of consumer and producer surpluses net of transaction costs. The model computes the market equilibrium, subject to a number of economic and biophysical constraints, including a market-clearing condition which states that the sum of imports, production, and manufactured supply of a given product in a given country must equal the sum of end-product consumption, exports, and demand for inputs in downstream manufacturing.

We linked successive yearly equilibria of the GFPM to reflect country-specific demographic and economic growth in accord with the IPCC SSPs. These pathways describe plausible development of socioeconomic futures, which focus on different challenges to climate-change mitigation and adaptation and their attendant effects on population and GDP (Fig. 2 and *SI Appendix*, Fig. S1 and Tables S3–S5).

We modeled country-specific land-use change assumptions under different SSPs as a function of evolving demographics and economic growth represented through an environmental-Kuznets-curve relationship with forest area. Other SSP parameters were captured within GDP and population projections and operationalized within the GFPM modeling framework through shifts in demand, supply, technological change, transportation and shipping costs, and freedom of trade (*SI Appendix, Global Forest Products Model*).

HWP Accounting. To calculate the annual emissions and removals of carbon from the HWP pool using historical data from FAOSTAT and projections provided by the GFPM, we followed the *2013 Revised Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol* (5) and applied them to all Annex I and non-Annex I parties. Results are sensitive to input data, and the IPCC outlines guidance related to three tiers of input availability. Following the default Tier 2 method, emissions from the HWP pool were assumed to follow a decay function, where the CO_2e stock of the j^{th} HWP {sawnwood, wood panels, and paper and paperboard} at the beginning of year t expands as new products enter the pool and contracts as existing products decay, according to the following equation:

$$\phi^j_{i,t+1} = e^{-k}\phi^j_{it} + \left[\frac{(1-e^{-k})}{k}\right] inflow^j_{it}, \quad [1]$$

where ϕ^j_t is the carbon stored in HWP j in year t in country i, k is a decay parameter ($k = \ln(2)/HL^j$) based on product j's half-life HL^j (*SI Appendix*, Table S6). Then, the carbon-stock change of HWP category j during year t is equal to:

$$\Delta\phi^j_{i,t} = \phi^j_{i,t+1} - \phi^j_{i,t}. \quad [2]$$

Following Decision 2/CMP.7 reached at COP17 in Durban, South Africa, in 2011, the IPCC *Good Practice Guidance* offers methods for estimating the inflow of carbon within these HWP groupings j, where credit is given only to the carbon stored in products produced from domestically sourced inputs. For simplicity, forest-management variables are dropped in the following equation due to limited availability of comprehensive global data and as it falls outside of the scope of the current analysis (25):

$$inflow^j_{it} = S^j_{it} * f^{DP}_{it}, \quad [3]$$

where S^j_{it} is the domestically produced HWP j in country i at time t, and f^{DP}_{it} is the share of domestic feedstock for the production of a particular HWP originating from domestic forests in country i at time t (*SI Appendix*, Fig. S2):

$$f^{DP}_{it} = \begin{cases} f^{IRW}_{it} \text{ for sawnwood and wood} - \text{based panels} \\ f^{IRW}_{it} * f^{PULP}_{it} \text{ for paper and paperboard} \end{cases}, \quad [4]$$

$$f^{IRW}_{it} = \frac{IRW^P_{it} - IRW^{EX}_{it}}{IRW^P_{it} + IRW^{IM}_{it} - IRW^{EX}_{it}}, \quad [5]$$

$$f^{PULP}_{it} = \frac{PULP^P_{it} - PULP^{EX}_{it}}{PULP^P_{it} + PULP^{IM}_{it} - PULP^{EX}_{it}}, \quad [6]$$

where f^{IRW}_{it} is the share of industrial roundwood for the domestic production of HWPs originating from domestic forests in country i at time t, and IRW^P_{it}, IRW^{IM}_{it}, and IRW^{EX}_{it} are the production, import, and export of industrial roundwood in country i at time t, respectively. Likewise, the annual share of domestically produced wood pulp as feedstock for paper and paperboard production in country i at time t is given by f^{PULP}_{it}, where $PULP^P_{it}$, $PULP^{IM}_{it}$, and $PULP^{EX}_{it}$ are the production, import, and export of wood pulp in country i at time t, respectively.

To include current-year carbon release from previously produced HWPs—referred to as "inherited emissions"—estimates before 1961 are needed. Since FAOSTAT data begins in 1961, the IPCC recommends extrapolating back to 1900 using the following equation:

$$V^j_{i,t} = V^j_{i,1961} e^{[U(t-1961)]}, \quad [7]$$

where V^j_t is annual production, imports, or exports of wood product j in year t in country i, and U is the estimated continuous rate of change of industrial roundwood production for a given region between 1900 and 1961 (*SI Appendix*, Table S7).

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