Global Carbon Mitigation Potential of Harvested Wood Products

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Carbon stored in harvest wood products (HWPs) is seen as a potential mitigation strategy, and countries have started to estimate their HWP carbon pool according to the latest IPCC guidelines. However, a solid estimate of country-level carbon pools and the global mitigation potential of HWPs has been lacking, making it difficult to ascertain how much countries can rely on HWPs in their climate policies. We estimated the HWP mitigation potential from 1961 to 2065 for 180 countries following IPCC carbon accounting guidelines, consistent with FAOSTAT historical data and plausible futures outlined by the Shared Socioeconomic Pathways. We found that the global HWP pool was a net sink of 335 Mt CO_2e yr^{-1}in 2015, and as much as 441 Mt CO_2e $yr^{-1}$by 2030. While HWPs offset sizeable amounts carbon emissions from industry, the HWP carbon pool is small compared to overall emissions (<1 %). Our results highlight many challenges countries face when including their HWP carbon pool to meet their international climate targets. An emissions gap persists under current IPCC *Good Practice Guidelines*as traded feedstock is ineligible for national GHG inventories, and could reach 120 Mt CO_2e $yr^{-1}$by 2065 with inequitable effects across regions. Mitigation estimates differ considerably among plausible future socioeconomic developments, and economic shocks can force HWPs to become a carbon source of emissions. While current accounting fails to acknowledge the full mitigation potential of HWPs, their potential compared to overall is miniscule even under the most optimistic assumption.

Carbon sequestration | Harvested wood products | Climate change | Forest sector | Shared Socioeconomic Pathways (SSPs)

Introduction

The carbon stored within harvested wood products is seen as a tool to mitigate climate change, yet its global potential as a carbon sink is both unknown and difficult to assess. In 2015, 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 for activities that have forest carbon benefits after forests are harvested, including carbon stored in harvested wood products. Yet, depending on the balance between carbon inflows and outflows, the harvested wood product pool can be either a carbon sink or source. Carbon is added to the harvested wood product pool when new products are produced, and released when older products reach the end of their useful life and are burned, or decompose in a landfill. 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 harvested wood product pool on regional and global scales. In general, income levels are expected to rise (2), as is population, at least until 2050 (3). Yet, beyond that, the future developments of socioeconomic factors are inherently uncertain, making the carbon mitigation potential of harvested wood products difficult to predict, and scenarios for different socioeconomic pathways necessary.

The consideration of harvested wood products as a tool to mitigate climate change is relatively new. The Intergovernmental Panel on Climate Change (IPCC) first recognized harvested wood products in their *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (4), but expressed a default assumption that "all carbon biomass harvested is oxidised 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 2011, at the seventeenth Conference of Parties (COP17), members concluded that harvested wood products made from domestic harvests can contribute towards 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*, adding harvested wood products as a mandatory pool to be reported within land use, land use change, and forestry (LULUCF) activities, and revised the reporting methods for the production approach to be employed during the second Kyoto period (5). Moving forward, countries are preparing to report their harvested wood product carbon pool within their Nationally Determined Contributions (NDCs) under the Paris Agreement.

In many countries, there has been an increase in carbon within the harvested wood product pool, according to historical data, including the United States (10), Portugal (11), Canada (12), Ireland (13), the European Union (14), Japan (15), and China (16). There may also have been similar historic trends across the globe (9,7), but available estimates rely on outdated accounting methods, and a global assessment of the HWP carbon pool under current accounting methods is lacking. Furthermore, it is unclear how the global HWP carbon pool will change in the future because only regional- or national-level estimates have

Significance

The carbon stored within harvested wood products (HWPs) may mitigate climate change, yet its global potential as a carbon sink is both unknown and difficult to assess. We show that in 2015, the global HWP pool was a net annual sink of 335 Mt CO_2e yr^{-1}, offsetting emissions for major industrial process emissions but only in some countries. By 2030, global HWP pool will reach 441 Mt CO_2e yr^{-1}. Furthermore, current IPCC carbon accounting guidelines cause a considerable gap between actual and reported emissions as traded feedstock is ineligible within national GHG inventories. However, the size of the poll greatly depends on future socioeconomic conditions, and economic shocks can quickly turn a country's HWP into a net source of emissions.

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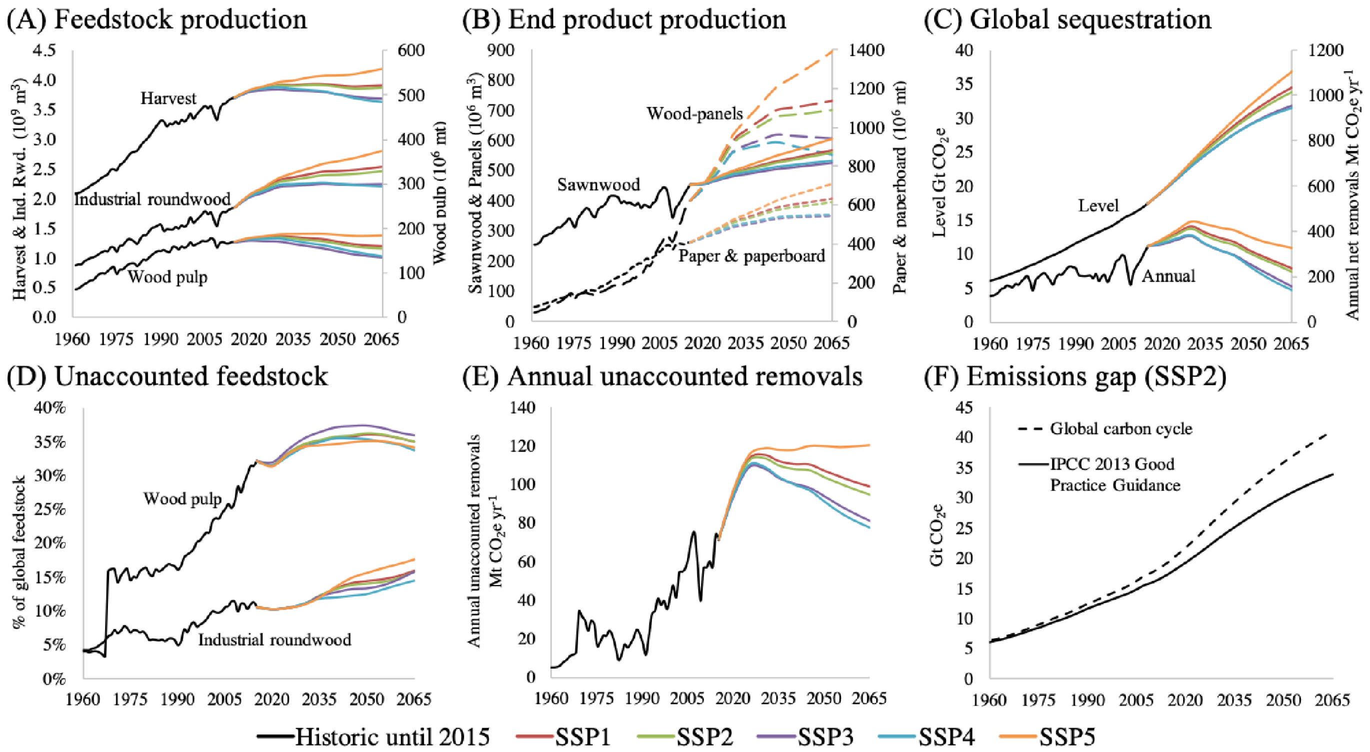

Fig. 1. . **Projected global harvested wood product market and carbon pool data for 1961 to 2015 from FAOSTAT, projections for 2016 to 2065 from the GFPM for SSP1-5**. Global production of feedstock (A) and end product groupings (B) drive the total level of carbon stored within harvested wood products, and the net annual carbon flux (year-to-year change) in the harvested wood product pool (C). 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). Consequently, a gap exists between the actual global carbon cycle of harvested wood products, and those inventoried under IPCC *2013 Good Practice Guidance*(E). Global Estimates are based on disaggregated country and commodity information.

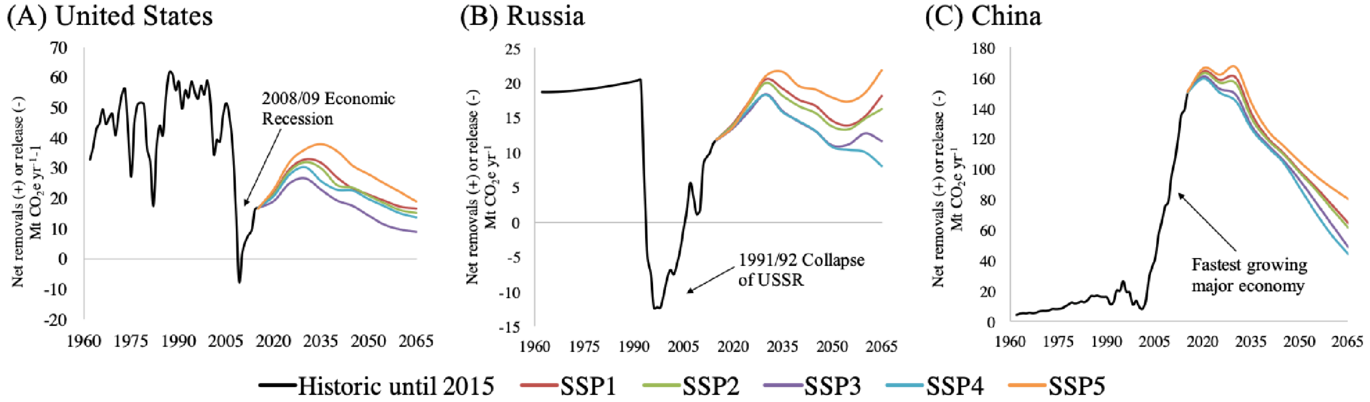

Fig. 2. . **Spatial patterns in socioeconomic and carbon pool information for 2015, and projections for 2065**. The first column shows income per capita, first for 2015 measured in GDP/capita purchasing power parity US$2005 dollars, and then in annual average growth rate from 2015 to 2065 for SSP2, SSP3, and SSP5. The middle column depicts the relative magnitude of the carbon pool in each country in terms of tCO_2per capita in 2015, and in 2065 for SSP2, SSP3, and SSP5. The final column depicts the annual carbon flux in each country in 2015, and in 2065 for SSP2, SSP3, and SSP5.

been made. and underlying future scenarios did not include economic models of future wood product markets (12, 14, 15). Consequently, the future potential of the HWP carbon pool is unknown, even though it is now mandatorily included within current IPCC *Good Practice Guidance*.

We contribute here the first comprehensive global estimate of the carbon mitigating potential of harvested wood products based on disaggregated country level data, as well as 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. 17), which provides a comprehensive collection of country level data on production, import, and export of forest products, beginning in 1961. In order to predict future trends in global forest product markets, we paired a publicly available economic model that is calibrated to FAOSTAT data (see *SI Appendix, Global Forest Products Model*) to five Shared Socio-economic Pathways (SSPs) that describe a series of different futures surrounding plausible demographic, economic, technological, social, governance and environmental factors (18-23). The development of international wood markets will play a critical role in the magnitude of the harvested wood product carbon pool within national GHG inventories.

We show that the harvested wood product pool is growing globally, but the size of the pool depends greatly on future socio-economic conditions. We also show that if trade was accurately

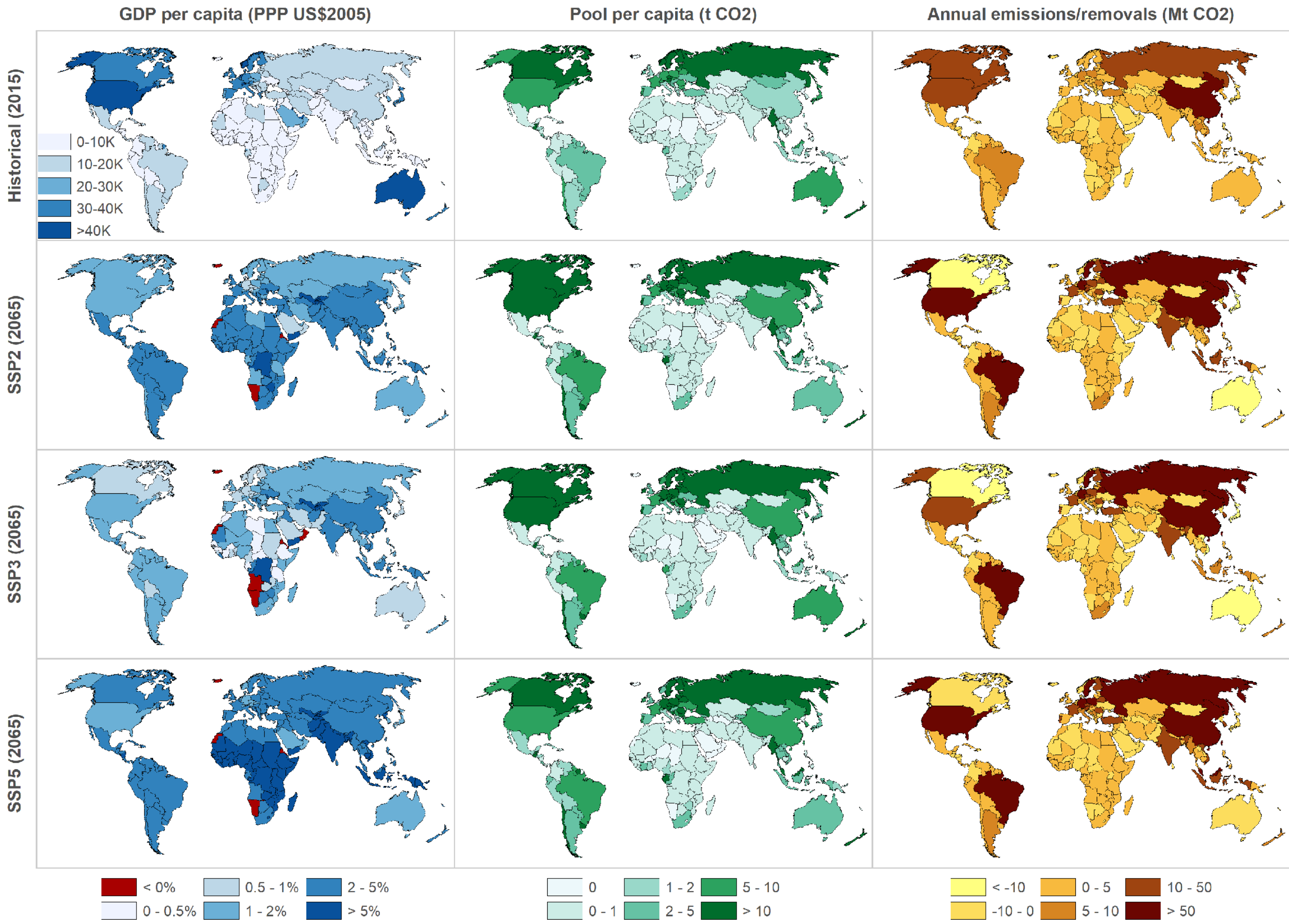

Fig. 3. . **Spatial patterns in degree with which the domestic harvested wood product pool could offset select IPCC emissions sectors**. Calculated as the ratio in the annual carbon flux in the harvested wood products pool to the reported UNFCCC GHG data for a given sector. 2015 data was used for all Annex I countries. For non-Annex I countries, the most recent available year's GHG emissions data was used, and matched to the annual carbon flux in the harvested wood products pool in that same year. See *SI Appendix*Table S15 for specific data and years used.

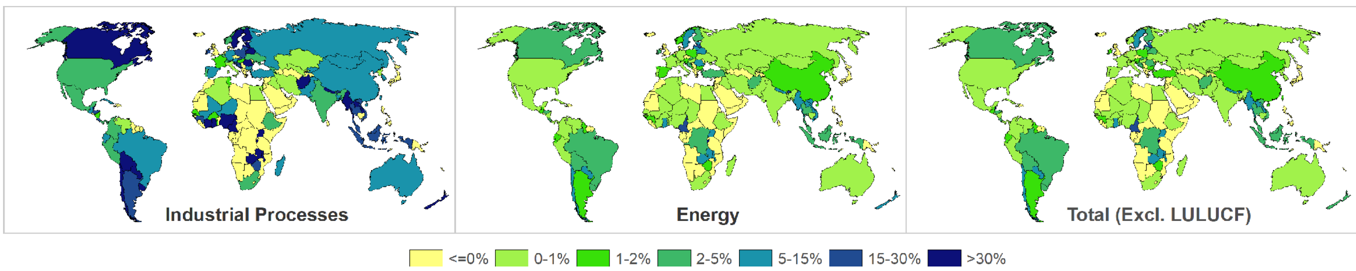

Fig. 4. . **The effects of economic shocks on the harvested wood product carbon flux in the United States (A), Russia (B), and China (C): for 1961 to 2015 from FAOSTAT; projections for 2016 to 2065 from the GFPM for SSP1-5**. The development of socioeconomic factors help determine production levels whereby carbon is added to the harvested wood product 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.

accounted for, the carbon mitigation potential of the world's harvested wood products could be even larger than what is reported under the current 2013 IPCC *Good Practice Guidance,* which includes only products produced from domestic harvests in national GHG inventories (see *SI Appendix, Harvested wood product accounting*). Consequently, our results suggest a considerable gap exists between the actual and the reported carbon pool under the current policy framework, and this gap may become larger in the future as markets become more closely integrated through trade. Furthermore, analysing 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 harvested wood product pool.

Results

Production of Wood Products. Global harvest and the production of wood products has risen markedly from 1961 to 2015 (Fig. 1A & 1B) according to FAOSTAT data, and our predictions show continued increases from 2015 to 2065 for all five SSPs, albeit at varying rates (*SI Appendix*, Tables S8-S13 present product and country/region level data). Specifically, global harvests have risen from 2.1 billion m^3 in 1961 to 3.72 billion m^3 in 2015 (Fig.

1A), and we project them to reach up to 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. 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 then remains stagnant through 2065. We predict similar trends for the global market for wood processing inputs like industrial roundwood and wood pulp (Fig. 1A; *SI Appendix*, Tables S8-S9), and these differences among SSPs make good sense because future harvests are ultimately driven by the demand for downstream products such as sawnwood, wood-based panels, and pulp and paper.

Global sawnwood production also strongly increased historically. Consumption in 1961 was 231 million m^3, rising to 454 million m^3 by 2015 (Fig. 1B; *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 sawnwood production to rise to 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 growth rate to start slowing around 2040 (Fig. 1B; *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 to 894 million m^3 for SSP4 and SSP5, respectively. Under the 'business-as-usual' SSP2 scenario, we project production to rise to 700 million m^3 by 2065. Production is predicted to continue to grow until 2065 under SSP1, SSP2 and SSP5, while it 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 to 407 million m^3 (Fig. 1B; *SI Appendix*, Table S12). We project this increase to continue by as much as 306 million m^3 of additional paper and paperboard production by 2065 years under SSP5, or as little as 139 million m^3 under SSP3. The 'business-as-usual' SSP2 scenario projects 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 rapidly, and faster than the contraction in printing and writing paper markets.

Carbon Flux in Harvested Wood Products. Carbon in the global harvested wood products pool has increased concomitantly with the increase in past production levels, and projections from 2015 to 2065 show similar trends but with considerable differences among the socioeconomic futures outlined by the SSPs (Fig. 1C). We project the amount of carbon stored within harvested wood products 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 carbon sequestration by this pool is estimated to peak around 2030 between 317 and 415 Mt CO_2e yr^{-1}, based on future socioeconomic conditions (Fig. 1C).

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 CO_2e yr^{-1} (Fig. 1C). In this scenario, GDP per capita is assumed to increase rapidly, and free trade results in a high level of wood product consumption. In stark contrast, SSP4 yields the lowest annual sequestration of 142 Mt CO_2e yr^{-1} by 2065, because of increasing economic disparities, and access to markets is limited in poor countries, curtailing overall production levels. The mitigation potential under the 'business-as-usual' SSP2 scenario results in a more moderate annual rate of sequestration of 220 Mt CO_2e yr^{-1} by 2065.

Annual mitigation estimates are also projected to vary over time within SSPs. Among SSPs, the standard deviation in the average annual rate of global sequestration from 2015 to 2065 is estimated to be ±13 Mt CO_2e yr^{-1}. However, across time estimates for SSP5 fall between 328 to 441 ±40 Mt CO_2e yr^{-1} during 2015 to 2065 due to high economic growth, where a world described by increasing inequalities under SSP4 leads to annual mitigation estimates between 142 and 383 ±82 Mt CO_2e yr^{-1} during this time. This highlights the need to have harvested wood product carbon removals occur at a rate that is sufficient to offset inherited emissions from historic production levels.

While aggregated global trends depict an optimistic picture in that the harvested wood products carbon pool is sequestrating carbon under all scenarios, and at every point in the future, we found strong variation at the country level (Fig. 2; *SI Appendix*, Table S13). We estimate that as of 2015, the highest annual carbon sequestration rates occur in timber-producing countries such as China, Canada, the United States, and Russia, and to a lesser degree in South American countries like Brazil and Scandinavian countries like Sweden, but this will likely change in the future. Canada, for example, was a net sink of emissions in 2015, but in 2065 reduced production of sawnwood and a shrinking pulp and paper industry will make current 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 harvested wood product pool in the future under some 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 Emissions Gap. According to the 2013 IPCC *Good Practice Guidance* accounting, only wood products produced from domestically sourced inputs can contribute to national GHG inventories, and exporting nations cannot claim carbon stored in end products in foreign nations. Consequently, there is a sequestration gap exists between what is actually stored in harvested wood products, and what is reported in national GHG inventories following IPCC *Good Practice Guidance*. In 2015, 10.5% of global industrial roundwood was traded and hence unaccounted for, as was 32% of wood pulp (Fig 1D). 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 in GHG inventories (for country level data see *SI Appendix*, Fig. S2).

Following IPCC *Good Practice Guidance*, this means that there is a substantial amount of non-inventoried carbon stored in harvested wood products. In 2015, we estimated 71 Mt CO_2e yr^{-1} of net carbon sequestered were unaccounted for, and this could grow to as much as 120 Mt CO_2e yr^{-1} by 2065 under SSP5 (Fig 1E). 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 harvested wood products global carbon cycle from that calculated using IPCC *Good Practice Guidance*. This gap is estimated to reach 4.8 Gt CO_2e by 2030, and as much as 7.3 Gt CO_2e by 2065 under the 'business-as-usual' SSP2 scenario (Fig 1F).

As international climate agreements are moving toward mandatory accounting for harvested wood product carbon flux, it is important to assess its relative importance by comparing its carbon flux against other IPCC emissions categories. The global annual carbon stored in the harvested wood products pool represents less than 1% of total GHG emissions (without LULUCF), but for some countries, it can be an effective tool to reduce national GHG inventories (Fig. 3). For timber rich regions like

Canada, harvested wood products 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 harvested wood products pool could offset an estimated 12% of energy emissions, 72% of industrial process emissions, or almost 9% of total emissions (without LULUCF). However, for many more countries, the harvested wood products 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. Hence, while the harvested wood products pool is a non-trivial carbon sink, and should be accounted for in climate accords, it is not substantial enough to offset larger sources of global emissions (for country level data see *SI Appendix*, Table. A15).

Effects of Economic Shocks. An additional challenge for countries that plan to rely on their harvested wood product carbon pool to meet their international climate targets has to do with the effects of economic shocks. The mitigation potential of harvested wood products is only realized if future market activity is sufficient to, at the very least, offset the decay from previously consumed products. Yet, there are a few historical examples where economic shocks have resulted in major changes in a country's harvested wood product carbon flux.

We estimated first the 2008/09 economic recession and its impact on the harvested wood product carbon pool of the United States. From 2007 to 2009, the U.S. consumption of sawnwood fell by 42%, plywood consumption by 32%, and paper consumption by 18%. Consequently, harvests in the U.S. fell from 425 million m^3 in 2007 to 332 million m^3 in 2009. This had major implications on the annual removals of carbon in the harvested wood product pool (Fig. 4A), causing a sharp drop in annual carbon sequestration in the harvested wood product pool, and resulting in a net source of emissions. However, since then, the U.S. economy has rebounded sufficiently to continue a trend of net annual removals.

A great example, where historic production rates are no longer met, is Russia, due to the collapse of the USSR in 1991, and its attendant effect on the carbon flux of Russia's harvested wood product pool (Fig. 4B). Immediately after the collapse, the Russian economy shrank by nearly 30%, followed by years of negative or no economic growth. Consumption of sawnwood in Russia, for example, fell from 47 million m^3 in 1991 to 15 million m^3 in 1997, with similar trends observed for other woods products. Consequently, Russia quickly transitioned from a net sink of carbon in their harvested wood product pool of 21 million Mt CO_2e yr^{-1} in 1991, to a net source of 13 Mt CO_2e yr^{-1} in 1995. Furthermore, unlike the rapid recovery of the U.S. economy after 2008/09, Russia has been plagued by this economic shock and the momentum of wood product decay for the subsequent decades.

Last but not least, one consequence of a rapid accumulation of carbon in the harvested wood products pool is that it builds momentum for high levels of future decay. A great example is the recent economic 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 has resulted in an exponential accumulation in carbon stored in harvested wood products. However, when China's economic growth rate slows into the future, the release of carbon from decaying products associated with the rapid growth period will outweigh the additions to the pool from future production, and we project a downward trend in future annual net sequestration in the harvested wood products pool (Fig. 4C). This means that if China wants to use the harvested wood products pool to mitigate other carbon emissions, it will need to sustain a high level of growth and hence wood production in order to ensure that its harvested wood product pool does not become a net source of carbon emissions due to decay.

Conclusion

We estimated the carbon mitigating potential of harvested wood products 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 Shared Socioeconomic Pathways. Our results suggest that global harvested wood product pool sequestered 335 Mt CO_2e yr^{-1} in 2015, and could sequester as much as 441 Mt CO_2e yr^{-1} by 2030 under favourable socioeconomic conditions.

Based on our results, the magnitude of carbon storage in harvested wood products can help to offset a non-trivial amount of industry process emissions for some countries, but is insufficient to mitigate the larger emission categories within energy and total GHG (excluding LULUCF). However, the harvested wood product pool is considerable, and should be integrated within global climate accords.

Global climate change agreements are moving towards more reliance on forestry to reduce atmospheric CO_2 levels, including consideration of harvested wood product carbon benefits, but caution should be exercised when integrating their carbon flux. The carbon mitigation potential of harvested wood products is quite sensitive to future socioeconomic conditions. In addition, economic shocks can cause a country's harvested wood products pool to transition from a net sink to a source of carbon, even for decades as seen in Russia. The degree to which current climate agreements are willing to accommodate for unforeseen economic shocks remains unknown. China, for example, is accumulating a substantial amount of carbon in their harvested wood products pool, which could become a liability if current levels of production and consumption decline.

Our analysis also highlights a global sequestration gap exists within current IPCC *Good Practice Guidelines* because traded feedstock is ineligible for national GHG inventories. In 2015, we estimated 71 Mt CO_2e yr^{-1} of ineligible removals resulted from current accounting methods. As trade is projected to expand under certain socioeconomic futures, this emissions gap could reach 120 Mt CO_2e yr^{-1} by 2065. This issue will also inequitably affect certain regions that have a market focused on feedstock trade.

Materials and Methods

Our analysis consists of two major parts: a) projections of future wood markets based on an economic model including an assessment of the implications of future socioeconomic conditions on wood product markets; b) and the attendant carbon flux within the harvested wood products 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. In order 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 United States Forest Service (26) and the United Nations FAO (27).

The GFPM was calibrated to closely replicate the most recent data reported by FAOSTAT by estimating input-output coefficients, and costs associated with manufacturing transportation. The GFPM solution for 2015 closely replicated the observations for the same year on production, consumption, prices, and net trade according to FAOSTAT. Elasticities of wood fiber supply come from (28), and demand elasticities for end products are from (29).

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 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 IPCCs Shared Socioeconomic Pathways. 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; *SI Appendix* Fig. S1, Tables S3-S5).

We modelled 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 are captured within GDP and population projections, and operationalized within the GFPM modelling framework through shifts in demand, supply, technological change, transportation and shipping costs, and freedom of trade (see *SI Appendix, Global Forest Products Model*).

Harvested wood product accounting. To calculate the annual emissions and removals of carbon from the harvested wood products 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). Following the Tier 2 method, emissions from the harvested wood products pool are assumed to follow a decay function outlined by the IPCC. That is, the CO_2e stock of the j^{th} harvested wood product {sawnwood, wood-panels, and paper & paperboard} at the beginning of year *t* expands as new products enter the pool, and contract as existing products decay according to the following equation:

$$\phi_{i,t+1}^{j} = e^{-k}\phi_{it}^{j} + \left[\frac{(1-e^{-k})}{k}\right] inflow_{it}^{j} \quad ,$$

where ϕ_t^j is the carbon stored in harvested wood product *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 harvested wood product category *j* during year *t* is equal to:

$$\Delta\phi_{i,t}^{j} = \phi_{i,t+1}^{j} - \phi_{i,t}^{j} \quad .$$

Following Decision 2/CMP.7 reached at COP17 in Durbin in 2011, the carbon stored in imported wood products is to be excluded in accounting for the carbon in three aggregate commodity groupings of sawnwood, wood-based panels, and paper and paperboard. Accordingly, the IPCC *Good Practice Guidelines* offer methods for estimating the inflow of carbon within these harvested wood product 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 (30):

$$inflow_{it}^{j} = S_{it}^{j} * f_{it}^{DP} \quad ,$$

where S_{it}^{j} is the domestically produced harvested wood product *j* in country *i* at time *t*, and f_{it}^{DP} is the share of domestic feedstock for the production of a particular harvested wood product originating from domestic forests in country *i* at time *t*:

$$f_{it}^{DP} = \begin{cases} f_{it}^{IRW} \; for\ sawnwood\ and\ wood-based\ panels \\ f_{it}^{IRW} * f_{it}^{PULP} \; for\ paper\ and\ paperboard \end{cases} \quad (4)$$

$$f_{it}^{IRW} = \frac{IRW_{it}^{P} - IRW_{it}^{EX}}{IRW_{it}^{P} + IRW_{it}^{IM} - IRW_{it}^{EX}} \quad (5)$$

$$f_{it}^{PULP} = \frac{PULP_{it}^{P} - PULP_{it}^{EX}}{PULP_{it}^{P} + PULP_{it}^{IM} - PULP_{it}^{EX}} \quad (6)$$

where f_{it}^{IRW} is the share of industrial roundwood for the domestic production of harvested wood products originating from domestic forests in country *i* at time *t*, and IRW_{it}^{P}, IRW_{it}^{IM}, and IRW_{it}^{EX} 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_{it}^{PULP}, where $PULP_{it}^{P}$, $PULP_{it}^{IM}$, and $PULP_{it}^{EX}$ are the production, import, and export of wood pulp in country *i* at time *t*, respectively.

In order to include current year carbon release from harvested wood products placed in use in previous years, which is referred to as "inherited emissions", estimates are needed for harvested wood products prior to 1961. Because the earliest year in the FAOSTAT data set is 1961, the IPCC *good practice guidelines* recommends extrapolating back to 1900 using the following equation:

$$V_{i,t}^{j} = V_{i,1961}^{j} e^{[U(t-1961)]} \quad ,$$

where V_t^j 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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