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Global forest products markets and forest sector carbon impacts of projected sea level rise

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ABSTRACT

Sea level rise (SLR) is among the climate-change-related problems of greatest concern, threatening the lives and property of coastal residents and generating far-reaching economic and ecological impacts. We project that SLR will lead to an increase in the rate of new housing construction to replace destroyed structures, impact global wood products supply and demand conditions, and cause changes in global forest sector carbon mitigation potential. Findings indicate that 71 million new units will be built by 2050 to accommodate the SLR-affected global population. More than two-thirds of these new units are projected to be in Asia. The estimated extra wood products needed to build these new residential units is 1,659 million m^3, assuming that all these structures would be built mainly with wood, representing a 4 % increase in total wood consumption, compared to projected reference level global wood products consumption. Increased timber removals to meet this higher construction wood demand (alternative scenario) is shown to deplete global forest carbon by 2 % by 2050 compared to the reference scenario. However, all such projected declines in forest biomass carbon could be more than offset by increased carbon sequestration in harvested wood products, avoided emissions due to substitution of wood for non-wood materials in construction, and biomass regrowth on forestland by 2050, with an estimated net emissions reduction benefit of 0.47 tCO_2e/tCO_2e of extra wood used in SLR-related new houses over 30 years. The global net emissions reduction benefit increased to 2.13 tCO_2e/tCO_2e of extra wood when price-induced changes in forest land area were included.

1. Introduction

Global sea level has risen over the past 200 years (Oppenheimer et al., 2019; Dangendorf et al., 2017; Kopp et al., 2017; Hay et al., 2015; Church et al., 2013) and is expected to continue rising throughout the 21st century and beyond (Oppenheimer et al., 2019; Siegert et al., 2020; Kopp et al., 2017). Causal factors, results of global warming, include thermal expansion of ocean waters and glacial and ice sheet melting (Oppenheimer et al., 2019; Frederikse et al., 2020; Kopp et al., 2014). Many studies conclude that global mean sea-level (GMSL) change over the 1900–1993 period ranged from an increase of 1.1 to 1.8 mm y^{-1} (Dangendorf et al., 2017; Hay et al., 2015; Church et al., 2013), with recent studies showing that the average annual rate from 1993 forward has increased to between 3 and 3.6 mm yr^{-1} (Oppenheimer et al., 2019; Dangendorf et al., 2017; Hay et al., 2015; Church et al., 2013). This acceleration in global sea-level rise (SLR) suggests rapidly expanding threats to human and natural systems in the near future, particularly if no actions are taken to reduce emissions or protect vulnerable people and property. How sea level will rise in the future depends on how global temperatures change, which directly depends on future trajectories of global greenhouse gas (GHG) emissions (Oppenheimer et al., 2019; Rasmussen et al., 2018; IPCC, 2014). Depending on the assumed pathways of future GHG emissions, GMSL is projected to rise by 0.4 m to 2.5 m by 2100 (Oppenheimer et al., 2019; Kopp et al., 2017; Kopp et al., 2014).

This projected rise in GMSL is based on current understandings of changing climate, including the effects of rising emissions, ocean processes, glacial and ice sheet melting, and ocean-land interactions. The largest contributions to GMSL in the 21st century will be glacial and ice sheet melting, raising concerns that with increasing warming, such

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melting could proceed more rapidly than in the past 20 years, influencing ocean mass and currents and pushing GMSL rises above current projections (Caesar et al., 2021; Siegert et al., 2020). Local sea level, the height of the water as measured along the coast relative to a specific point on land, could differ substantially from the GMSL rise (Ward et al., 2020; Kopp et al., 2014), with variations from location to location depending on differences in factors such as vertical land motion relative to changes in sea level and on the effects of tides, currents, and winds (Oppenheimer et al., 2019). Adequately quantifying local sea level changes will require improved information on coastal surfaces and better understanding of local processes (Ward et al., 2020). Consequently, the probability of coastal flooding and its associated social, economic, and ecological impacts can vary substantially across coastal regions, even with a relatively small change in GMSL (Kopp et al., 2017; Kopp et al., 2014).

One certainty with respect to SLR is that overall coastal hazard exposures of social, economic, and ecological systems will increase in the coming decades. Coastal hazards include permanent inundation; increased frequency and intensity of flooding from storm surges; increased coastal erosion; expanded saltwater intrusion into soil, ground, and freshwater resources; more impeded drainage; and greater losses and degradation of coastal ecosystems and natural resources, including forests and wetlands (Oppenheimer et al., 2019; Kearney et al., 2019; Kulp and Strauss, 2019; Desmet et al., 2018; Jevrejeva et al., 2018; Diaz, 2016; Brown et al., 2011). About 10 % of the global population (more than 600 million people) live in coastal areas that are less than 10 m above sea level (United Nations, 2017a). Rising sea levels are therefore inexorably exposing an increasing share of this population to increased coastal flooding risk (Kulp and Strauss, 2019), damaging and destroying existing built environments and making migration (managed or forced) to inland regions inevitable (Desmet et al., 2018; Hauer et al., 2016).

Efforts to quantify the effects of SLR on human and natural systems have been increasing. Policy makers seek information on the magnitudes of such impacts as a foundation for proposed actions to respond to the many challenges created by climate change in general (e.g., curbing GHG emissions) and SLR in particular (plan and invest in adaptation strategies to protect and mitigate damage to coastal systems). Many policy- and economics-related SLR studies have quantified the direct economic costs of SLR using the Dynamic Interactive Vulnerability Assessment (DIVA) modeling framework (Jevrejeva et al., 2018; Nicholls et al., 2018; Diaz, 2016; Hinkel et al., 2014; Brown et al., 2011). DIVA assesses biophysical and socio-economic consequences, such as coastal flooding, land loss, salinization, and forced migration and their corresponding economic costs (Vafeidis et al., 2008). Direct economic cost estimates using the DIVA framework suggest projected impacts on the order of multiple trillions of dollars, which translate to annual losses of 0.3 % to 10 % of global GDP by 2100, depending on projected emissions trajectories and associated rise in sea level, and that such costs could be reduced substantially (by a factor of up to 10) with appropriate adaptation strategies in place (Jevrejeva et al., 2018; Nicholls et al., 2018; Diaz, 2016).

Although these studies provided valuable insights to likely costs of SLR-related damages and costs and benefits of investment in adaptation activities, less visible in their analyses are potential economic interactions and feedbacks between various sectors of the broader economy and how SLR impacts might affect supplies of and demands for the factors of production, prices, consumption, production, and trade. Such evaluations of markets are enabled through use of a market equilibrium analytical framework. Several studies have utilized market equilibrium analysis frameworks to evaluate the economy-wide direct and indirect effects of coastal flooding due to SLR (Schinko et al., 2020; Desmet et al., 2018; OECD, 2015; Darwin and Tol, 2001). For example, Schinko et al. (2020) evaluated direct and indirect economic effects of coastal flooding due to SLR and adaptation under medium- and low-emissions Representative Concentration Pathways (RCPs) scenarios described in van Vuuren et al. (2011). This study projected that construction, agriculture, and energy-intensive industry sectors would be most affected by SLR-related destruction of capital stock, leading to production losses globally, although the service sector would be less affected. Darwin and Tol (2001) demonstrated how direct cost estimates of SLR that ignore the effects of a loss of factor endowments on consumer prices can lead to an underestimate of global economic impacts of SLR, and they reported that direct cost estimates ignored the role of international trade in redistributing some losses from high-impact regions to low-impact regions. OECD (2015) revealed that the magnitude of SLR damages experienced in any particular region would depend in part on the ability of economies to adapt through changes in production technologies, consumption patterns, and international trade. Desmet et al. (2018) showed how spatial economic adjustments of SLR impacts can mitigate direct losses experienced in a specific location. They found that coastal population shifts, driven by SLR-driven amenity changes, would reduce global real GDP in present value terms by 0.16 % to 0.25 % and cause economic surplus (welfare) declines by 0.21 % to 0.31 % by 2150, depending on the degree of projected SLR. The relatively lower projected economic losses in their study, compared to others already cited, were due to the anticipated SLR-induced spatial shifts of economic activity in the global economy.

Despite the accumulation of studies evaluating the economic impacts of SLR across various markets and economic sectors, no study has investigated its potential economic impacts on the global forest sector. Forests and associated forest products industries are recognized as important parts of the global economy, with an estimated direct economic contribution of US $600 billion yr^{-1} in global income and 13 million jobs (FAO, 2014). The sector is additionally responsible for similarly large indirect and induced economic impacts, so that total contributions exceed one trillion dollars and 45 million jobs (Li et al., 2019). Forests also provide a wide range of environmental goods and services that are not traded in a typical market and are therefore difficult to value monetarily, such as protecting soil and water, sequestering atmospheric carbon, providing wildlife habitat, esthetic benefits, and recreational opportunities. For example, Costanza et al. (1997) estimated the total economic value of ecosystem services provided by global forested landscapes to be US$ 4.7 trillion per year or $ 969 per ha, most of which were in the form of non-market values.

SLR threatens the provision of all such environmental goods and services, in two ways: First, increased flooding can lead to the disappearance of or altered composition and structure of coastal and adjacent forest resources (White et al., 2022; Williams et al., 1999; Kearney et al., 2019; Strain, 2014; Doyle et al., 2010). Such potential SLR-related losses in coastal forest (mainly mangrove (*Rhizophora* spp.)) and adjacent forest areas could negatively affect forest biomass carbon. However, Smart et al. (2020) reported that aboveground carbon declines along the coastline are likely to be offset by aboveground carbon gains further inland due to natural succession and forest management activities such as tree planting. Additionally, SLR-induced contraction in forests can affect forest product markets by shifting supply backwards and raising timber prices, reducing forest products output and therefore also harvested wood products carbon. Second, SLR can lead to increased demand for wood products for use in new residential construction that will need to be built to accommodate increasing numbers of coastal residents who would migrate to inland regions (Hauer et al., 2020; Desmet et al., 2018; Hauer et al., 2016) in the face of permanent inundations or higher rates of annual flooding risks (Kulp and Strauss, 2019; Rasmussen et al., 2018; Neumann et al., 2015). Increased demands to rebuild have impacts that are not necessarily tied to coastal regions but instead are felt more broadly, reaching inland to alter harvesting activity in non-coastal timber growing regions, changing conditions of demand, supply and international trade in wood product markets, and affecting the level of overall carbon sequestration services that forests provide. Higher wood product demands by the construction industry can lead to increased forest product prices, which can impact the competitive advantage of a country to harvest timber and to produce, consume, and trade in forest products (UNECE/FAO, 2021; Nepal et al., 2019). Changes in timber harvests and manufacturing activities can affect carbon mitigation by the forest sector via changes in forest stocks, carbon stored in harvested wood products, and avoided fossil carbon emissions resulting from substitution of wood for more carbon-emissions-intensive non-wood materials in construction, such as steel and concrete (UNECE/FAO, 2021; Amiri et al., 2020; Johnston and Radeloff, 2019; Nepal et al., 2016).

This study investigates potential SLR-induced demand, supply, and trade dynamics in the forest sector and associated impacts on overall forest sector carbon. We tackled these questions using a global spatial partial market equilibrium analysis (Global Forest Products Model, GFPM, Buongiorno, 2015; Buongiorno et al., 2003) and a consequential life cycle analysis (CLCA) framework. We employ GFPM to address how the global forest sector responds to changes introduced by the impacts of SLR on residential housing and on coastal forest area (mainly mangrove) globally. Specifically, we used the most recent projections of populations vulnerable to SLR under different scenarios of GHG emissions and SLR reported by Kulp and Strauss (2019) to make adjustments to the GFPM. We introduced increases in wood products demand by estimating the number of new residential housing units (and wood products) needed by populations that would move from threatened coastal areas. We also included decreases in coastal forest area by estimating loss due directly to SLR. We chose to focus on mangroves because the area and location of these forests globally are available (Hamilton and Casey, 2016) and current studies suggest that these forests are being lost under local SLR rates (Friess et al., 2019) and will be threatened under future SLR (Saintilan et al., 2020). We adjust the model to include the loss of almost all current mangrove forests in each country (Hamilton and Casey, 2016) by 2050 in both the reference and alternative scenarios. The projected consequences of such SLR-induced increase in wood demand and contraction in mangrove forest area are indicated by their projected impact (relative to a reference scenario) on prices, production, consumption, and trade quantities of 14 different products. The projected consequences also include changes to global forest sector carbon stocks and emissions. These carbon changes are evaluated using CLCA (Nepal et al., 2016; Skog et al., 2014). CLCA estimates the change in environmental impacts due to a change in product output, in contrast to attributional life cycle analysis (ALCA), which estimates environmental impacts to make, use, and dispose of one unit of product (Cherubini et al., 2012). The net carbon emissions impact of increased wood use in SLR-related new residential units was evaluated by estimating projected changes in three major carbon pools: 1) carbon sequestered in forest biomass, 2) carbon stored in harvested wood products, and 3) avoided manufacturing emissions due to substitution of wood for non-wood materials in new housing units.

Insights provided by this study can help policy makers develop plans and strategies to minimize the overall negative impacts of SLR on the economy and forest sector carbon.

2. Materials and methods

The study linked five key pieces of information to assess global and country-specific impacts of SLR on the forest sector. A new model was developed to relate future SLR-related increases in new residential housing unit construction and its wood product needs, in conjunction with SLR-related losses of mangrove forests. The model was combined with a global forest sector model, the GFPM (Buongiorno, 2015; Buongiorno et al., 2003). Three primary pieces of country-specific information were needed to construct the new model: 1) the forecasted coastal population vulnerable to projected SLR, 2) estimates of new residential housing units needed to house the SLR-vulnerable populations and the wood needed to build new units, and 3) estimates of mangrove forest area loss in each country. The augmented GFPM was used to run 1) a reference scenario where it is assumed that replaced housing units lost due to SLR will be built with wood in the same proportions that they are built today and mangrove forest area will be lost to SLR, and 2) an alternative scenario where it is assumed that all new housing needed to replace lost housing units will be built of wood and mangrove forest area will be lost to SLR. For each scenario, the model provided projections for key variables: 1) forest area, forest stock (inventory), timber removals, prices, and quantities of wood products consumed, produced, and traded; 2) projected carbon stored in forest biomass, carbon stored in harvested wood products in end uses (HWP); and 3) estimates of fossil emissions avoided due to substitution of wood for non-wood materials in new housing units built to accommodate SLR-vulnerable populations. The subsequent sections provide further details on how such information was obtained and analysed.

2.1. Projected population vulnerable to sea level rise

We utilized results from the comprehensive assessment of global coastal population vulnerability due to SLR provided by Kulp and Strauss (2019), who combined Kopp et al.'s (2017; 2014) sea level projection data for 2050 and 2100 for low, moderate and high emissions pathway scenarios represented under the Intergovernmental Panel on Climate Change (IPCC)-inspired RCPs 2.6, 4.5, and 8.5 (van Vuuren et al., 2011, Table 1), and new, more accurate digital elevation data based on NASA's Shuttle Radar Topography Mission (SRTM) Version 3.0. Kulp and Strauss (2019) substantially enhanced the accuracy of elevation data in coastal areas by correcting for errors in SRTM data (between 1 and 20 m) attributable to topology, vegetation, buildings, and random noise, enabling more accurate prediction of the coastal inhabitants vulnerable to SLR. Specifically, the authors converted their error-corrected coastal elevation data to reference high tide lines and compared these with the projected SLR to find areas that could permanently fall under the new high tide lines. In addition, the authors identified areas with high flooding risk by comparing the projected local flood risk statistics approximating the one-year return level water height and the water heights of such flood events with projected SLR. Finally, they determined the number of people living today in areas identified within the risk of permanent exposure to higher tide line and to local annual flood risk, providing an estimate of the total population vulnerable to SLR in each country. As summarized in Table 1, the forecasted populations affected by SLR are available for 2050 and 2100 for three RCPs, based on two models of local sea-level projections. The first set of projections (Kopp et al., 2014) was informed by expert community assessment, expert elicitation and process modeling, and note that the Antarctic ice sheet was the dominant source of variance at many sites in late 21st century projections. The second set of projections (Kopp et al., 2017) includes additional information on physical processes influencing ice sheet melt contributions to SLR, resulting in higher projected SLR after 2050. Note that the populations affected by SLR are forecasted to increase and vary widely across emissions and SLR scenarios by 2100, but they are very similar across those scenarios through 2050. We chose to use the forecasted numbers for 2050 because our focus was on evaluating the medium-term impacts of SLR on the global forest sector. We used 2050 population at risk projections for the RCP 8.5 scenario by Kopp et al. (2017) (column 13 in Table 1).

2.2. Estimating sea level rise-related new housing units and wood usage

We translated the forecasted population at risk due to projected SLR by 2050 for the RCP 8.5 scenario (Table 1) to estimate additional housing units potentially needed to accommodate those affected populations (Table 2). We then used a combination of data sources and assumptions (Tables 2–4) to estimate the quantities of additional sawnwood and wood-based panels needed to build those housing units in individual countries (Table 5). Specifically, the quantities of sawnwood and wood-based panels needed to build SLR-related new housing units were derived from information summarized in Tables 2–4. Table 2

Table 1
Forecasted population (millions) vulnerable to sea level rise (mean values), 2050 and 2100, in the top 20 affected countries (by forecasted population) under different emissions and SLR scenarios (Source: Kulp and Strauss, 2019).

Emissions scenario[3]	Present day	Population (millions) at risk based on sea-level projection of Kopp et al. (2014)[1]						Population (millions) at risk based on sea-level projection of Kopp et al. (2017)[2]					
		RCP 2.6		RCP 4.5		RCP 8.5		RCP 2.6		RCP 4.5		RCP 8.5	
Global mean sea level rise (cm)		24	49	26	59	29	79	23	56	26	91	31	146
Country/region		2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100
World	250.00	300.00	340.00	300.00	360.00	300.00	390.00	290.00	350.00	300.00	400.00	300.00	480.00
China	81.00	93.00	100.00	93.00	110.00	94.00	120.00	92.00	110.00	94.00	120.00	95.00	140.00
Bangladesh	28.00	42.00	56.00	42.00	57.00	43.00	60.00	42.00	57.00	42.00	63.00	43.00	70.00
India	31.00	35.00	41.00	36.00	42.00	36.00	44.00	34.00	40.00	34.00	44.00	35.00	51.00
Vietnam	28.00	31.00	33.00	31.00	34.00	31.00	36.00	30.00	34.00	31.00	37.00	31.00	42.00
Indonesia	20.00	23.00	27.00	23.00	29.00	24.00	31.00	23.00	28.00	24.00	34.00	24.00	40.00
Thailand	8.00	12.00	13.00	12.00	14.00	12.00	14.00	11.00	13.00	11.00	14.00	11.00	15.00
Philippines	5.40	6.70	8.10	6.80	8.60	6.90	9.50	6.60	8.50	6.80	10.00	7.00	13.00
Netherlands	4.90	5.50	5.90	5.50	6.20	5.60	6.80	5.40	6.10	5.50	7.30	5.60	8.80
Japan	4.10	5.20	6.50	5.30	7.10	5.40	8.50	5.20	6.90	5.30	9.30	5.50	15.00
Egypt	4.00	4.20	4.50	4.20	4.60	4.20	4.90	4.20	4.50	4.20	5.00	4.20	5.30
UK	3.20	3.60	3.80	3.60	4.00	3.60	4.30	3.50	4.00	3.60	4.60	3.70	5.40
Myanmar	2.60	3.20	4.10	3.30	4.30	3.30	4.90	3.20	4.10	3.20	5.20	3.30	6.80
Iraq	2.40	2.60	2.90	2.70	3.00	2.70	3.10	2.60	2.90	2.60	3.20	2.70	3.50
Malaysia	1.40	2.20	2.70	2.30	2.90	2.30	3.40	2.20	2.90	2.30	3.70	2.40	4.90
USA	1.50	2.00	2.60	2.00	2.90	2.10	3.40	2.00	2.90	2.10	4.10	2.20	6.30
Taiwan	1.10	1.90	2.20	2.00	2.30	2.00	2.80	1.90	2.30	2.00	3.10	2.00	4.00
Germany	0.89	1.60	1.60	1.60	1.70	1.60	1.80	1.60	1.60	1.60	1.80	1.60	2.00
Brazil	0.47	1.40	1.60	1.40	1.70	1.40	2.00	1.40	1.70	1.40	2.10	1.40	3.40
S Korea	0.16	1.30	1.50	1.30	1.60	1.30	1.80	1.30	1.50	1.30	2.00	1.30	2.80
Nigeria	0.10	1.20	1.40	1.20	1.40	1.20	1.60	1.20	1.40	1.20	1.60	1.20	2.30

1 Kopp et al. (2014) projections represent the probabilistic projection of SLR, informed by a combination of expert community assessment, expert elicitation, and process modeling.
2 Kopp et al. (2017) projections used here are DP16, probabilistic projections that have been enhanced with a small ensemble of Antarctic ice-sheet (AIS) simulations that incorporate mechanisms such as ice shelf hydro-fracturing and ice-cliff collapse, resulting in higher projected SLR especially after 2050.
3 RCP2.6 is a low emissions concentration pathway for CO_2-equivalent by 2100, RPC 4.5 is a moderate emissions pathway, and RCP 8.5 is a high emissions pathway (van Vuuren et al., 2011).

Table 2
The top 20 countries (by forecasted population) at risk of SLR by 2050 (Kulp and Strauss, 2019), and the authors' estimated corresponding numbers of household units affected due to SLR.

Region	Total population[1]	SLR-affected population[1]	Share of affected population		Affected household
	Millions	Millions	%	Persons/unit	Millions
World	**6,800**	**300.00**	4 %		**67.64**
China	1,300	95.00	7 %	3.92	24.26
Bangladesh	160	43.00	27 %	4.94	8.70
India	1,200	35.00	3 %	4.97	7.04
Vietnam	90	31.00	34 %	4.36	7.12
Indonesia	240	24.00	10 %	4.37	5.50
Thailand	67	11.00	16 %	4.71	2.34
Philippines	100	7.00	7 %	4.97	1.41
Netherlands	17	5.60	33 %	2.27	2.47
Japan	130	5.50	4 %	2.54	2.16
Egypt	80	4.20	5 %	4.86	0.86
UK	62	3.70	6 %	2.36	1.57
Myanmar	53	3.30	6 %	4.22	0.78
Iraq	30	2.70	9 %	7.70	0.35
Malaysia	28	2.40	9 %	4.76	0.50
USA	310	2.20	1 %	2.75	0.80
Taiwan	23	2.00	9 %	N/A	N/A
Germany	82	1.60	2 %	2.10	0.76
Brazil	200	1.40	1 %	4.30	0.33
S Korea	49	1.30	3 %	2.93	0.44
Nigeria	150	1.20	1 %	4.76	0.25

Note that the countries are ordered by the projected size of population affected by SLR.
1 Kulp and Strauss (2019).
2 United Nations (2017b).

provides information on the size of the SLR-affected population for each country, average household sizes, and the estimated new housing units needed to accommodate the affected populations. Tables 3 and 4 present data and assumptions regarding the proportion of new housing units built with wood and the intensity of wood used in wood-framed housing units, respectively.

The estimates of new housing units needed to be built to accommodate the SLR-affected population in each country (Table 2) was

Table 3
Literature reported and assumed share of wood-framed housing units in different countries used for this study.

Country	Proportion of wood-framed houses	Source	Assumed in this study	
			Reference scenario	Alternative scenario
US	90–94 %	Gustavson et al., 2006; CEI-Bois, 2010.	92 % (avg. of reported)	100 %
Canada	76–85 %	Gustavson et al., 2006.	80.5 % (avg. of reported)	100 %
Japan	45–93 %	Maki and Tanaka, 2014; CEI-Bois, 2010.	69 % (avg. of reported)	100 %
Nordic countries	45–85 %	Gustavson et al., 2006; CEI-Bois, 2010.	65 % (avg. of reported)	100 %
Europe	8–10 %	CEI-Bois, 2010.	10 %	100 %
Germany	10 %	Gustavson et al., 2006.	10 %	100 %
Netherlands	6–7 %	Gustavson et al., 2006.	10 %	100 %
France	4 %	Gustavson et al., 2006.	10 %	100 %
Scotland	60–70 %	Gustavson et al., 2006; CEI-Bois 2010.	N/A	100 %
United Kingdom	20 %	Gustavson et al., 2006.	20 %	100 %
Australia	81–92 %	Kapambwe et al., 2009.	86 % (avg. of reported)	100 %
All other countries	Not Available		10 %	100 %

Table 4
Literature reported and assumed intensity of wood use in SLR-related new housing units used for this study.

Country	Assumed m^2/unit	Source / Remark	Assumed m^3/m^2	Source / Remark
US	100	Median square footage of single unit of US multifamily unit in 2015 (US Census Bureau, 2020)	0.41 (79 % sawnwood, 14 % str. panel, 7 % non str. panel)	Average use in single and multi-family units (McKeever and Howard, 2011)
Canada	Same as US		Same as US	
Japan	Same as US		Same as US	
Nordic countries	Same as US		Same as US	
Europe	Same as US		Same as US	
Germany	Same as US		Same as US	
Netherlands	Same as US		Same as US	
France	Same as US		Same as US	
Scotland	Same as US		Same as US	
United Kingdom	Same as US		Same as US	
Australia	Same as US		Same as US	
All other countries	Same as US		0.15	Average use in Malaysia and Honduras (Koenigsberger, 1971)

obtained by dividing the forecasted population at risk of SLR in 2050 under RCP 8.5 (Kulp and Strauss, 2019, Table 1) by the current average household size (persons/unit) in that country (United Nations, 2017b, Table 2). The amounts of wood use in those housing units were then estimated using the information on the proportion of houses built of wood (Table 3) and on the floor area and the intensity of wood usage (m^3/m^2) in those units (Table 4). We assumed for the purposes of this study that the average floor space of new housing units would be 100 m^2 (1,074 ft^2), a figure based on the median floor space constructed in 2015 in an individual unit within a multifamily housing structure in the United States (US Census Bureau, 2020). The intensity of wood use in wood-framed construction varies depending on country and building design, which can range from as low as 0.2 to as high as 0.6 m^3 per m^2 of installed floor space, especially in temperate countries (Hurmekoski, 2017), with lower intensities reflecting those applicable to light frame structures (e.g., in Sweden) and higher intensities representing mass-timber-based structural frames in high rise buildings (e.g., in Central Europe) (Hurmekoski, 2017). This analysis used the approximate midpoint of that range (0.41 m^3/m^2) for temperate countries and a much lower intensity for tropical countries (about 0.15 m^3/m^2), based on the estimated wood usage in wooden houses built in Malaysia and Honduras (Koenigsberger, 1971). It was further assumed that about 79 % of wood used in wooden houses was sawnwood, 14 % was plywood, and 7 % was fibreboard, based on the historical average wood usage in single- and multifamily housing units in the United States (McKeever and Howard, 2011). Nevertheless, we acknowledge that our assumptions about the use of wood in multifamily structures simulated for the purposes of this study ignore variation in unit sizes and wood content in multifamily buildings across sizes of structures, adding unmodeled uncertainty to our calculations.

The projected wood consumption in those estimated new housing units were estimated for a reference scenario and an alternative scenario (Table 5), which served as target inputs to the Global Forest Products Model (GFPM, discussed in the next section).

2.3. Reference and alternative scenarios

The reference scenario represents the scenario where new residential housing units built to replace those lost by the SLR-affected population would be constructed based on recent historical proportions of wood-frame construction where such use is known (including the United States, Canada, Sweden, Finland, the UK, Australia, and Japan, which currently build 45 % to 92 % of new housing with wood) or, if not known, that 10 % of new housing units would be built with wood-frame construction. In other words, this scenario represents the scenario where most of the countries build with a low share of wood-framed housing units.

In contrast, the alternative scenario represents the scenario where all SLR-related new residential housing units are assumed to be built mainly of wood. While the proportion of SLR-related new housing units that would be built of wood in the future is unknown, this scenario enables us to establish an upper-bound on the potential quantity of wood consumed for new construction, given rising seas, by comparing the model outcomes driven by the wood needed to build all new SLR-related housing units primarily with wood vs the wood needed to build those units based on known historical proportions or assumed lower proportions. Note that wood here refers to finished wood products (sawnwood and wood-based panels combined).

To provide a sense for the overall effects to the global forestry sector from SLR and new housing, we first ran GFPM under a business-as-usual scenario (GFPM base model), where the GFPM runs were driven only by projected income and population under Shared Socioeconomic Pathway (SSP) scenario 2 (O'Neill et al., 2017), without sea level rise impacts. The estimated quantities of finished wood products consumed in the reference and alternative scenarios provided the target input for use in the GFPM to determine sea level effects on residential housing units and

Table 5
GFPM projected combined consumption of sawnwood and wood-based panels in the Shared Socioeconomic Pathway 2 (GFPM base model without the effect of SLR), and the authors' estimated demand for sawnwood and wood-based panels for use in SLR-related new housing units construction in the reference and the alternative scenarios, 2020–2050.

Country/ Region	SLR related new homes	Reference scenario wood consumption[1]	Alternative scenario wood consumption[2]	Wood consumption without SLR (GFPM base model)[3]	Reference scenario cumulative wood consumption including the GFPM base model consumption (Col 3 + Col 5)	Alternative scenario cumulative wood consumption including the GFPM base model consumption (Col 4 + Col 5)	Additional wood consumption (Col 6-Col5 or Col 4-Col 3))	% Increase relative to reference scenario
	millions	*million m*^{3}	*million m*^{3}	*million m*^{3}	*million m*^{3}	*million m*^{3}	*million m*^{3}	*%*
World	**71**	**285**	**1,944**	**40,231**	**40,516**	**42,175**	**1,659**	**4.1**
Top 20 countries	**67**	**273**	**1,860**	**30,208**	**30,480**	**32,067**	**1,587**	**5.2**
China	23.7	97	974	16,828	16,925	17,802	876	5.2
Bangladesh	8.5	13	127	20	32	147	115	354.6
India	7.2	11	109	770	781	879	98	12.5
Viet Nam	7.1	11	107	581	591	687	96	16.2
Netherlands	2.4	10	99	161	171	260	89	52.4
Indonesia	5.3	8	79	406	413	485	71	17.2
UK	1.5	13	63	731	744	794	50	6.7
Japan	2.1	59	85	795	854	881	26	3.1
Thailand	2.5	4	38	141	145	179	34	23.8
Germany	0.8	3	31	1,000	1,004	1,032	28	2.8
Philippines	1.4	2	21	111	113	131	18	16.4
S. Korea	0.4	2	18	324	326	342	16	5.0
France	0.4	2	16	612	614	628	14	2.3
Iraq	0.4	1	14	38	39	52	13	32.8
Egypt	0.9	1	13	265	266	278	12	4.4
Myanmar	0.8	1	12	87	88	99	11	11.9
Italy	0.2	1	9	498	499	507	8	1.6
Malaysia	0.5	1	7	205	205	212	7	3.2
USA	0.7	27	30	5617	5,645	5,647	2	0.0
Canada	0.2	6	8	1,018	1,024	1,026	2	0.2

Note that the countries are ordered by the projected quantities of SLR-induced additional wood demand.
[1] Assumes SLR-related new homes are built based on a historical proportion of wood-framed homes in countries where data are available, or 10% of those new homes are built mainly of wood in countries where no information on wood usage is available or where wood usage is low.
[2] Assumes all SLR-related new homes are built mainly of wood.
[3] Does not consider the effect of SLR. Demand for wood products is driven by income and population projected in the Shared Socioeconomic Pathway 2.

the associated wood usage. We iteratively ran the GFPM model (with SSP2 income and populations as wood demand drivers) until the target additional consumption of finished wood under the reference and alternative scenarios (Table 5) were met. The difference in model outcomes between the reference and alternative scenarios, after the given additional wood consumption target is met, provided the estimates of the upper bound effects of increased wood usage in SLR-related new housing units. Table 5 compares the additional quantities of finished wood consumed in the reference and alternative scenarios, with the projected quantities of finished wood consumed under the GFPM base model represented by SSP2 income and populations.

As presented in Table 5, the top 20 countries affected by SLR are estimated to consume about 278 million m^3 and 1,860 million m^3 of finished wood in the reference and alternative scenarios, respectively, resulting in the additional increase in finished wood consumed of 1,587 million m^3 (1,659 million m^3 when all countries affected by SLR are considered) when new housing was constructed primarily with wood. Given the projected 30,208 million m^3 of wood that would be consumed under the GFPM base model (SSP2) cumulatively between 2020 and 2050, this extra finished wood consumption due to SLR represents an increase of 5.25 % relative to wood consumption in the top 20 countries affected by SLR (or a 4 % increase relative to global wood consumption in the reference scenario when all countries affected by SLR is considered).

2.4. Estimating sea level rise-related loss of coastal forest area

Increased flooding and salinization due to rising seas will affect both coastal forest ecosystems, such as mangrove forests, and forests adjacent to coastal ecosystems. Forests near but not immediately adjacent to coastal seas are likely to be affected by sea level, but little quantitative information is available on the nature of the effect or rate of impact, suggesting that these ecosystems are unlikely to be lost at large scales by 2050. However, mangrove forests are seen as particularly threatened by SLR because of their coastal and low-lying locations (Friess et al., 2019). Although mangroves have some adaptive capacity to react to SLR, Saintilan et al. (2020) reported that mangroves were unable to persist, based on the paleorecord of mangrove forest expansion and retreat, when the local SLR or relative SLR (RSLR) rates exceeded 6.1 mm per year. Citing Church et al. (2013) and Kopp et al. (2017), Saintilan et al. (2020) report that RSLR is expected to exceed 5 mm y^{-1} by 2030 and 7 mm y^{-1} by 2050 under a high-emissions scenario in low-latitude mangrove settings. For this analysis, we assume this RSLR for all mangrove forests on all coasts, and the loss of mangroves by 2050 globally. Under these simplifying assumptions, our analyses considered the effects of potential SLR-related losses of mangrove forests in each country. The losses were modelled by forcing the GFPM (described in the next section) to gradually lose equal amounts of mangrove forest area each year in each country such that almost all the current mangrove forest area in each country (reported by Hamilton and Casey (2016)) is lost by 2050. Note that the total global mangrove forest area in 2014 was 7.6 million ha (Hamilton and Casey, 2016), which represented less than 0.2 % of the total global forest area (the sum of total forest area of 180 countries modelled in GFPM is 3,976.21 million ha, FAO (2015)).

The estimated new finished wood products consumption levels, based on the combination of data and assumptions described above, was used to outwardly shift the demand curves for these products in the GFPM (described in next subsection) by an amount equal to the wood needed to build new homes for people displaced by SLR. We assumed that wood use per unit floor area that occurs in the reference scenario would still occur in the alternative scenario. That is, they would be inelastic with respect to increases in wood product prices. Although price increases may have some effect on wood use per unit floor area or the floor area per unit, we chose to use the same floor area per unit and wood use per unit floor area in both the reference scenario and alternative scenario to see a likely upper bound on market and carbon effects. The shifts in demand curves used for both scenarios resulted in new equilibrium quantities and prices, production, consumption, and international trade of various forest products. The differences in these market variables for 14 forest products between the reference and the alternative scenarios of wood demand shifts and reduced mangrove forest area (same in reference and alternative scenarios) under SLR described the magnitude and direction of impacts on the global forest sector of SLR.

2.5. The global forest products model (GFPM)

This study utilized the most recent version of the GFPM (Buongiorno, 2015; Buongiorno, 2015), a spatial partial equilibrium model (Takayama and Judge, 1971; Samuelson, 1952) of the global forest sector, to obtain the projections for each of a reference scenario and an alternative scenario of future wood use of market clearing prices and quantities of consumption, production, and trade of 14 categories of forest products. In addition to providing multi-year projections of these market variables, the GFPM provides multi-year projections of forest area, forest growth, and forest inventory in 180 countries. The model projection covered 2020–2050, with 2017 being the base year. The calculated market equilibrium quantities and prices of commodities are such that they maximize the consumers' and the producers' surplus for all products and countries, given a number of economic and biophysical constraints (SI Appendix 1). The simulation of the global forest resources and the forest product markets is enabled in the GFPM through the integration of timber supply (production of raw materials), processing industries (manufacturing of materials into products), demand for end products, and trade. GFPM has been applied in numerous studies related to national, regional, and global forests and forest products sector including the FAO's 1999 global forest products outlook study (Zhu et al., 1998), U.S. Department of Agriculture (USDA) Forest Service's 2010 RPA Assessment (USDA Forest Service, 2012), the 2012 North American Forest Sector Outlook (UNECE/FAO, 2012), and numerous journal publications evaluating the impacts of various environmental and trade policies on global, regional, and national forest sectors (e.g., Johnston and Radeloff, 2019, Buongiorno and Johnston, 2018; Nepal et al., 2016; Nepal et al., 2015). GFPM is freely available to the public for research purposes at https://buongiorno.russell.wisc.edu/gfpm/.

A detailed description of the model structure, parameters, and mathematical formulations is available in Buongiorno (2015). Here, we provide a brief description of how the GFPM models demand, supply, production, consumption, and trade of various wood products as well as forest growth, forest stocks and forest area for individual countries. The supply of industrial roundwood, which is the only input to sawnwood and wood-based panels (plywood, particleboard, and fibreboard) and a major input to wood pulp production for use in manufacturing paper products (newsprint, printing and writing paper, and other paper and paperboard), is modelled as a function of its own price and forest stock, both of which are projected endogenously. The demands for different manufactured products in each country are modelled as functions of their own prices and exogenously projected gross domestic product (GDP) for the country. The production quantities of intermediate and final manufactured products are determined by the specified manufacturing costs and their respective input–output coefficients (units of industrial roundwood required to produce a unit of manufactured product) in each country. Trade of forest products (imports and exports) is modelled between a country and the rest of the world. Quantities of products produced, imported or exported are driven by the competitive advantage of a country or a region in producing and shipping each product. Competitive advantage is a function of transport costs, manufacturing costs, input–output coefficients, and the endogenously solved domestic and world prices of a product. Forest land use (forest area) in each country is projected in the GFPM as a quadratic function of GDP per capita and its squared term, based on the Environmental Kuznets Curve (EKC) approach (Kuznets, 1955). The current functional form implies that annual rate of forest area change is negative at low GDP per capita, becomes positive and increases at higher GDP per capita, and then decreases and approaches zero at very high GDP per capita (Turner et al., 2006). Forest stock, which shifts industrial roundwood supply (harvests) in each country, evolves over time as the previous year's stock quantity plus the projected current year growth quantity minus the roundwood harvest quantity. Forest stock growth (net of mortality) before harvest is modelled as a nonlinear function of forest stock density, which implies that forest growth increases with declining stock density and decreases with increasing stock density (Turner et al., 2006). Changes in forest stock density are determined by the projected changes in forest stock and forest area.

All economic and biophysical data and parameters between the reference and the alternative scenarios were kept the same in GFPM (including losses of mangrove forests), except for the estimated quantities of extra wood demanded in both scenarios (which exogenously shifted the demand curves of wood products in GFPM, providing solutions of new equilibrium quantities and prices). Thus, projected differences in model outcomes between the reference and the alternative scenarios can be attributed as impacts on forests and the forest products sector of increased wood use in SLR-related new housing construction.

2.6. Estimating forest sector carbon

The GFPM projected changes in forest stock in each scenario and country provided the inputs needed to estimate carbon sequestered in living forest biomass, whereas the projected production and trade quantities of manufactured products served as the inputs for estimating carbon stored in harvested wood products in end uses across countries and scenarios. Estimates of carbon in above- and below-ground forest biomass are based on the methods presented in Johnston et al. (2019), which rely on the observed ratio of above- and below-ground biomass carbon and forest stock (SI Table S10) data in individual countries and regions reported in the Global Forest Resource Assessment report (FAO, 2015). Carbon stored in HWP in each country was estimated using the IPCC suggested production accounting approach (Johnston et al., 2019; Rüter et al., 2019), which includes carbon stored in end use wood products (sawnwood, wood-based panels, and paper and paperboard products) that were made using wood harvested in a country (and includes exported wood products from a country). It excludes carbon stored in imported wood products in end uses. Finally, the avoided fossil emissions from wood products in place of non-wood products in construction in the alternative scenario were estimated using an average displacement factor (a measure of how much greenhouse gas emissions would be avoided if a wood-based product is used instead of another product to provide the same function). The displacement factor is from Sathre and O'Connor (2010), who synthesized 21 published studies that provided information on emission offsets due to substitution of wood for non-wood materials in construction. The avoided emissions factor they estimate is 2.1 kg C/kg C in wood products.

3. Results

3.1. Estimated new housing units and wood usage

Our analyses suggested that the forecasted population needing to move due to projected SLR could increase demand for housing by about 71 million new residential units globally (about 68 million units in the top 20 SLR-affected countries) by 2050 (Table 2). This number of units, 2.37 million yr^{-1}, represents the equivalent of adding the housing demands of two new countries the size of the United States to the world.

Consistent with the forecasted population needing to move due to SLR (Kulp and Strauss, 2019) and UN data on current family members per household in various countries (United Nations, 2017b), we estimated that China would need about one-third (24 million) of the new housing units, followed by Bangladesh (9 million), India and Vietnam (7 million each), Indonesia (5 million), and Japan, Thailand, and the Netherlands (2 million each) (Table 2). The reference scenario assumes that new housing units would be built in response to SLR, but the proportion built using wood is the same as the current proportion of housing built of wood (45 % to 92 %) for countries such as the United States, Canada, Sweden, Finland, the UK, Australia, and Japan, and assumes for the rest of countries needing new housing, that 10 % of new housing would be built of wood. These are countries where information on wood use in construction was either not available or minimal (Tables 3 and 4). Using the assumed allocations of new housing units to each country, China was estimated to consume more than half (876 million m^3) of the extra finished wood products (sawnwood and wood-based panels) needed for the alternative scenario relative to the reference scenario, followed by Bangladesh (115 million m^3), India (98 million m^3), Vietnam (96 million m^3), the Netherlands (89 million m^3), Indonesia (71 million m^3), and the UK (50 million m^3) (Table 5).

3.2. Projected global forest product market impacts

Our analyses projected a 2.3 % increase in global industrial roundwood production (Fig 1 and SI Table S1), 2020–2050, relative to the projected timber harvest level in the reference scenario over the same period (a 2020 to 2050 cumulative quantity of 86,898 million m^3). The increased timber harvest was driven by the production of extra quantities of sawnwood (1,265 million m^3, SI Table S2) and wood-based panels (313 million m^3, SI Table S3) globally. The increased global industrial roundwood harvest was accompanied by a 3 % increase in the average global industrial roundwood price (Fig 2) and a projected decline in global forest stocks (standing inventory volumes) of 2 % (1.5 billion m^3, SI Table S5) by 2050, relative to the reference scenario level for prices and stocks, respectively. The projected price increase for industrial roundwood and increased demand for sawnwood and wood-based panels in construction in the alternative scenario led to a slight reduction in global paper and paperboard production (29 million metric tons, or about 0.2 % less) (SI Table S4) because of roundwood diversion to wood products.

In contrast to the global level outcomes, the projected changes in industrial roundwood and manufactured wood products production in individual countries varied according to a country's comparative advantage in producing and trading products. Countries with strong comparative advantage expanded wood products production to meet domestic demand and/ or to export to countries with increased demand. Countries with weak comparative advantage meet most of their demand by increasing imports (SI Table S1-S4). For instance, China was projected to meet its higher wood consumption needs for sawnwood (685 million m^3, SI Table S2) and wood-based panels (184 million m^3 SI Table S3) by expanding its domestic production by 70 % and 100 %, respectively. However, China produced almost half of its needed sawnwood and panel products by increasing use of industrial roundwood imports for domestic production of sawnwood and wood-based panels (341 million m^3 more imported, compared to the reference level) and the remaining half by increased domestic harvests (360 million m^3). In contrast, countries such as Japan and the UK respectively met 87 % to 100 % of their extra sawnwood consumption needs by importing more sawnwood (SI Table S2). Most other countries expanded their domestic production of sawnwood and wood-based panels, mainly by expanding their domestic industrial roundwood harvests. Other countries, such as the United States, Sweden, Australia, Brazil, Russia, France, and Malaysia, increased industrial roundwood net exports to meet international import demand by Asia, reflecting their greater trade competitiveness of industrial roundwood, given SLR-induced increases in the world price for industrial roundwood. For instance, the United States increased its industrial roundwood net exports by 198 million m^3, 2020–2050, in the alternative scenario, meeting 10 % of extra global industrial roundwood demand in the alternative scenario, with other countries increasing their net exports by 6 to 59 million m^3 (SI Table S1).

Our analyses indicated a projected increase in the combined value of global industrial roundwood, sawnwood, wood-based panel products, and paper products of $1.2 trillion (3 %) during 2020–2050 (Table 6), due to SLR-induced increases in prices for forest products, about 36 % of which was projected to be shared by industrial roundwood suppliers (forest landowners, SI Table S6) and the rest by the producers of manufactured wood products (SI Tables S7-S9). The price increase for industrial roundwood resulted in slightly lower global production of paper and paperboard products, but their price increases made its value of production incrementally higher (by $3.5 billion), compared to the reference scenario (SI Table S9). Almost two-thirds of the SLR-induced increased value of production was shared by industrial roundwood producers and sawnwood and wood-based panels manufacturers in Asia, with the rest shared by Europe (18 %), North/Central America (11 %), South America (3 %), and Oceania and Africa (1 % each) (Table 6).

3.3. Projected global forest sector carbon impacts

Our results showed how SLR-related changes in timber harvests and product manufacturing activities altered the amounts of carbon stored in forests and harvested wood products (HWP) by major world region

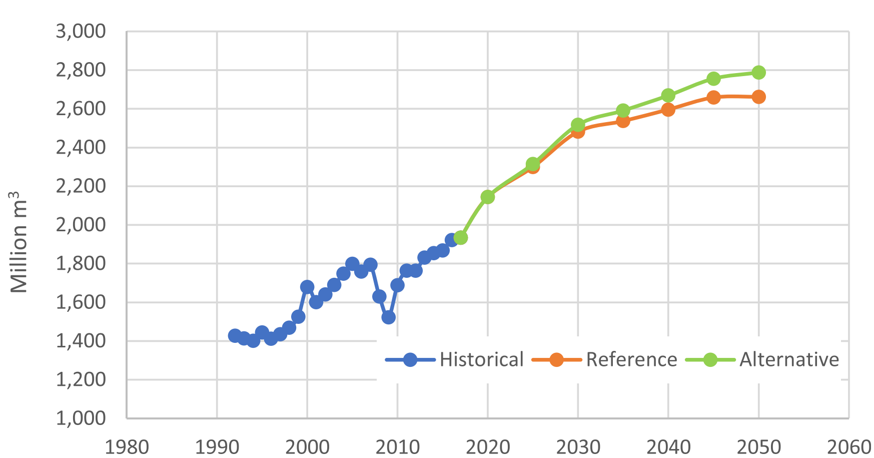

Fig. 1. Historical and projected global industrial roundwood production under the SLR-related reference (current rate of wood use) and alternative (high wood use) scenarios, 2020-2050.

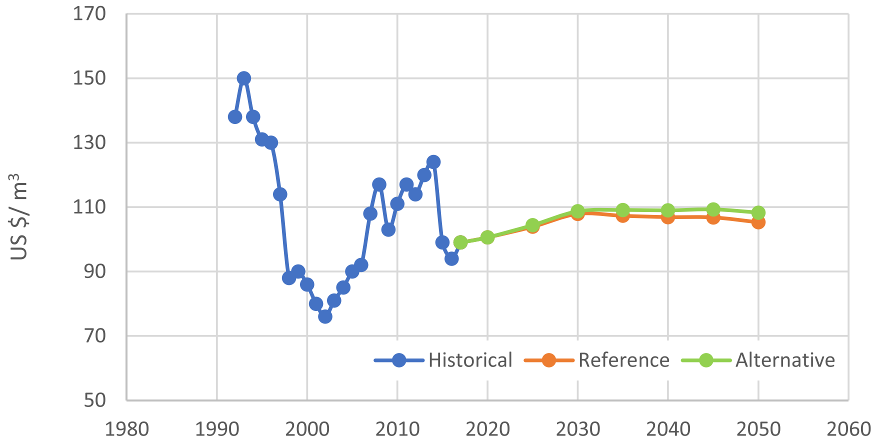

Fig. 2. Historical and projected global industrial roundwood price under the SLR-related reference (current rate of wood use) and alternative (high wood use) scenarios, 2020-2050.

Table 6
Projected combined value (billions of 2018 US dollars) of industrial roundwood, sawnwood, wood-based panels, and total paper and paperboard production, 2020–2050, under the SLR-related reference (current rate of wood use) and alternative (high wood use) scenarios in world regions and selected countries.

	Cumulative value (2020–2050)		Change in the alternative scenario relative to the reference scenario
Region/Country	Reference	Alternative	
AFRICA	698	705	7
N/C AMERICA	7,734	7,869	135
Canada	1,702	1,749	47
US	5,426	5,509	83
S AMERICA	2,404	2,439	34
Brazil	1,540	1,561	22
ASIA	21,162	21,954	792
Bangladesh	25	269	244
China	14,500	14,878	378
India	1,552	1,576	24
Indonesia	1,084	1,122	37
Japan	1,197	1,207	10
Malaysia	332	339	7
Thailand	447	467	20
Vietnam	404	441	37
OCEANIA	584	601	17
Australia	346	351	6
EUROPE	11,056	11,279	223
Finland	884	892	9
France	742	754	12
Germany	1,608	1,641	32
Netherlands	154	155	1
Russia	2,004	2,049	45
Spain	411	421	10
Sweden	969	985	16
UK	406	415	9
Top 20 SLR-affected countries	**31,466**	**31,901**	**968**
WORLD	**43,638**	**44,846**	**1,209**

(Table 7) for the alternative scenario relative to the reference scenario. The projected changes in forest biomass carbon in a country, 2020 to 2050, is the result of the net effect of timber harvests and biomass regrowth on standing forest stock. Carbon stored in HWP is the direct outcome of storing carbon in end uses (sawnwood, wood-based panels, and paper and paperboard). We did not include wood carbon stored in solid waste disposal sites (SWDS) after use or fossil emission offsets by burning wood after use. The substitution effect of wood products is the result of emissions avoided by using wood products in place of fossil carbon emissions-intensive non-wood products in construction. Our results showed that increased timber harvests in the alternative scenario would result in lower global timber inventory relative to the reference level. Global forest biomass carbon stocks would be lower by 2.87 billion metric ton (t) of CO_2e by 2050, representing a 2 % reduction relative to the projected reference level carbon stock in 2050 (Table 7). However, the results also show that net reductions in the forest biomass carbon (which includes regrowth) could be offset by the combined effects of increased carbon sequestered in HWP in housing and increased levels of avoided carbon emissions from the substitution of wood in construction for non-wood materials. Almost 38 % of the projected relative reduction in forest biomass carbon could be offset by increased carbon stored in HWP by 2050 (1.09 billion tCO_2e). Taking into account the emissions offset with increased substitution of wood in construction resulted in additional avoided emissions of 2.29 billion tCO_2e, offsetting more than 80 % of the projected global loss in forest biomass during 2020–2050 (Table 7). The net global carbon emissions reduction considering these three pools was 0.51 billion tCO_2e by 2050, providing an estimated global displacement factor of 0.47 tCO_2e per tCO_2 of extra wood. Stated differently, each additional tCO_2e in wood products used in SLR-related new housing units, would lead, for the average unit of wood used over the projection period, to 0.47 tCO_2e net less emissions to the atmosphere by 2050.

These projected global results mask important regional level differences due to changes in timber harvests, manufactured wood products output, and the associated changes in forest growth and stock brought about by SLR-induced higher demand for wood products. For example, all major world regions showed a net increase in carbon emissions except for Asia, suggesting that change in forest stock growth, HWP carbon, and avoided emissions from substitution were not enough to offset the projected loss in the forest biomass carbon in those regions due to increased harvesting. The largest increase in net carbon emissions was observed in North/Central America (0.48 billion t less CO_2e, relative to the reference level), followed by South America (0.19 billion t less CO_2e), Europe, Africa and Oceania (Table 7). These net increases in carbon emissions are mainly an outcome of increased harvests of industrial roundwood by countries for export or export of domestically produced sawnwood and wood-based panels (mostly to Asia), which were not offset by projected biomass re-growth in domestic forests and increased carbon stored in HWP. Also contributing to net emissions is the assignment of the benefit of avoided emissions to the regions using the wood for housing (mostly Asia), not the regions supplying the wood (e.g., North America).

4. Discussion and conclusions

This study contributes to new understanding of the potential effects of SLR on global forest product markets and on global forest sector

Table 7
Projected changes in carbon (billion tCO_2e) stored in forest biomass, harvested wood products, and avoided carbon emissions due to substitution of wood for non-wood materials in construction under the SLR-related reference (current rate of wood use) and alternative (high wood use) scenarios.

	Forest Biomass C		HWP C		Avoided Emissions due to substitution		Net C Balance	
	Change (2020–2050)	Change relative to the reference scenario	Change (2020–2050)	Change relative to the reference scenario	Change (2020–2050)	Change relative to the reference scenario	Change (2020–2050)	Change relative to the reference scenario
AFRICA								
Reference	−7.55		0.25		0.94		−6.36	
Alternative	−7.64	−0.08	0.25	0.00	0.96	0.01	−6.43	−0.07
N/C AMERICA								
Reference	15.87		0.73		3.23		19.83	
Alternative	15.31	−0.55	0.80	0.08	3.23	0.00	19.35	−0.48
S AMERICA								
Reference	−27.53		0.79		1.07		−25.67	
Alternative	−27.73	−0.19	0.81	0.01	1.07	−0.01	−25.86	−0.19
ASIA								
Reference	128.00		9.13		23.16		160.28	
Alternative	126.57	−1.43	9.92	0.80	25.19	2.04	161.69	1.41
OCEANIA								
Reference	3.03		0.10		0.33		3.46	
Alternative	2.95	−0.08	0.11	0.02	0.33	0.00	3.40	−0.06
EUROPE								
Reference	30.95		4.35		2.95		38.26	
Alternative	30.42	−0.53	4.54	0.19	3.20	0.25	38.16	−0.10
Top 20 SLR-affected countries								
Reference	105.64		10.25		25.73		141.62	
Alternative	103.61	−2.03	11.17	0.92	28.09	2.35	142.87	1.24
WORLD								
Reference	142.77		15.35		31.69		189.80	
Alternative	139.89	−2.87	16.44	1.09	33.98	2.29	190.31	0.51

carbon. By estimating a global displacement factor, this study also contributes to an understanding of the net carbon emissions impacts of using extra wood in new residential housing units worldwide. Key insights from the analysis include how population projected to be exposed to risk of SLR in individual countries necessitates the construction of new residential housing units as those populations shift inland for their safety and economic wellbeing. Our analysis projects a need for about 71 million new housing units to be constructed globally by 2050, suggesting an economic opportunity in the global construction sector and its supply and value chains worldwide, in concurrence with the findings of Schinko et al. (2020). The global wood products sector relies heavily on demand from residential construction in several countries, including the United States, Canada, Nordic nations, Australia, and Japan. In countries where wood use in construction is relatively low at present (e.g., most of the tropical countries), SLR presents an avenue for expanding wood use in new residential construction, which would substantially offset global net carbon losses caused by higher wood product demand and lost mangrove forests. The analysis also reveals that projected increases in product prices would alter the comparative advantages of countries. Higher wood product demand in countries with high wood needs for rebuilding would lead to lower relative comparative advantages in international trade. These findings suggest that SLR not only may affect the wood product markets of a country where more housing is built, but also can affect the forest products markets of other countries (without a SLR-affected population) via international trade. Implications for the global forest sector are that global markets can add to or counterbalance the forest products market and carbon effect of SLR on a country via SLR-induced changes in product prices and production (e.g., see Schinko et al., 2020; Darwin and Tol, 2001). Our analysis suggests that increased use of wood in SLR-induced new housing units would lead to increased forest sector revenues (via increased product prices and outputs), which can help counterbalance potential negative economic impacts of SLR in the sector (e.g., gradual loss of coastal and adjacent forest area due to flooding and salinization). Projected loss of coastal wetlands (mangroves and other ecosystems) has ranged from 20 % to 90 % (Schuerch et al., 2018). The likelihood of losing all mangroves by 2050 will depend on many factors, such as local rates of SLR, availability of sediment, and accommodation space for mangroves to move. Under the high-emissions scenario (RCP 8.5), relative SLR is expected to exceed the tolerance of mangroves in low-latitude settings by 2050 where rates of SLR are expected to be higher than the global average (Saintilan et al., 2020). The scenario of losing all mangrove forests allowed us to follow the implications of such loss through local and international trade, as well as carbon implications. We also carried out additional model runs without implementing mangrove forest area losses and compared the outcomes with the presented results, which considers gradual declines of mangrove forest areas, 2020–2050, in both the reference and alternative scenarios. We found negligible changes in market outcomes, as expected, between the with and without mangrove forest loss cases, which can be explained by mangrove's small share in global total forest area (less than 0.2 %).

Similarly, we found reduced total global forest biomass carbon stock in the mangrove forest loss cases, as expected (about 115 million t less CO_2e by 2050). We did not incorporate the effects of other forest losses in adjacent coastal ecosystems. Sea level rise can impact forests adjacent to coastal grasslands and forests through storm surges and the gradual increase in salinization of fresh water and ground water. Ghost forests (standing dead trees) are reported primarily along the Atlantic coast of North America, where SLR is currently greater than the global average (Smart et al., 2020; Kirwan and Gedan, 2019; Schieder and Kirwan, 2019). Only small-scale studies on the effect on these adjacent forests are available, limiting a global perspective. In planning efforts where forest retention is a concern, expert opinion has been used to assess the potential loss of these forests (Greene et al., 2020). Thus, the lack of information on large-scale loss of adjacent forests due to SLR suggests that this effect globally seems less likely, given the SLR and timeframe considered in this analysis. We note that although mangrove forests loss had very small forest carbon impacts globally by 2050, the potential loss in soil carbon due to mangrove forests could be substantial (Sanderman et al., 2018). To get a sense of magnitude of soil carbon loss due to mangrove forest losses, we utilized the ratio of forest area and soil carbon data for individual country reported in the 2015 global forest resource assessments (FAO, 2015), consistent with the methods presented by Johnston et al. (2019). Using such ratios, we find that about 377 million metric t of soil carbon stock would be lost with the projected loss of mangrove forests, representing 0.22 % of global soil carbon stock in 2015. However, our results would be unimpacted by this estimated loss in soil carbon because we considered mangrove forest area losses both in the reference and the alternative scenarios, thus the projected effects are net of potential soil carbon losses due to projected loss of mangrove forests in individual countries.

In addition to identifying market effects, our analysis also indicated that increased demand for wood products can alter net carbon emissions at global, regional, and national levels by altering the amount of standing timber stock, the quantities of manufactured wood products carbon stored in HWP in housing and the emissions offset by use of wood versus alternative materials for housing. Our analysis indicates that using wood in all SLR-related new residential housing worldwide would more than offset reduced forest biomass carbon resulting from increased harvests, with an estimated net carbon benefit of 0.51 billion tCO_2e over a 30-year period (Table 7).

Although the estimated carbon benefit seems small, it should be viewed from three different angles to get a better perspective. First, let us assume a case where all new units are built with non-wood materials. In such a case, an estimated 1.5 to 3.2 billion tCO_2e would be emitted to the atmosphere. The low-end estimate is based on the estimated average embodied emissions (total greenhouse gas warming potential (GWP) from resource extraction to a completed residential building shell) per square meter (m^2) of two typical residential single-family houses constructed mainly with concrete and steel in the U.S. cities of Atlanta and Minneapolis (Lippke et al., 2004), which was estimated at 191 kg CO_2e per m^2. The high-end estimate is based on the estimated average emissions per m^2 of two high-rise multifamily residential housing units constructed in China mainly with concrete (Zhang et al., 2020), giving rise to estimated Scope 1 emissions (emissions due to processes of manufacturing materials, components, and building equipment) of 459 kg CO_2e per m^2. Our analysis indicates that using wood in all new units not only avoids embodied emissions associated with use of non-wood materials (1.5 to 3.2 billion tCO_2e), but also adds to the total net carbon savings of 0.51 billion tCO_2e (after taking into account reduced forest biomass carbon of 2.87 billion tCO_2e due to increased timber harvests). Thus, the estimated difference in net carbon emissions between using wood in all new units versus using non-wood materials in those new units globally can vary between −0.28 billion tCO_2e (low-end emissions associated with building homes with non-wood materials) to 1.42 billion tCO_2e (high-end emissions associated with building homes with non-wood materials), over 30 years, suggesting that there is high uncertainty in the estimated carbon benefits of increased wood use in SLR-related home construction.

Second, given the estimated HWP C increase of 1.09 billion tCO_2e resulting from increased wood products use in residential units, our estimated 0.51 billion tCO_2e of net reduction in carbon emissions gives rise to an estimated global average displacement factor of 0.47 tCO_2eper tCO_2e of extra wood over 30 years. That is, for every additional ton of CO_2e in wood used in SLR-related new housing units worldwide, there is an average net carbon emissions reduction of 0.47 tCO_2e during 2020–2050. These finding suggests that increasing use of wood in residential construction leads to carbon savings (or at least it does not contribute to carbon emissions), in contrast to using non-wood materials, which only contributes to carbon emissions. The displacement factor could be an underestimate because we did not include what happens with the wood after its use life in housing. It could be stored for a longer time in SWDS or it could be burned and offset fossil carbon emissions. These C storage and emission offset benefits could be

Table 8
Projected net carbon effects (billion tCO_2e) of SLR-related reference (current rate of wood use) and alternative (high wood use) scenarios, considering timber-price-induced indirect effects on forest land use[1].

	Forest Biomass C		HWP C		Avoided Emissions due to substitution		Net C balance	
	Change (2020–2050)	Change relative to the reference scenario	Change (2020–2050)	Change relative to the reference scenario	Change (2020–2050)	Change relative to the reference scenario	Change (2020–2050)	Change relative to the reference scenario
AFRICA								
Reference	−7.54		0.25		0.94		−6.35	
Alternative	−7.30	0.24	0.25	0.00	0.96	0.01	−6.09	0.26
N/C AMERICA								
Reference	16.22		0.73		3.23		20.18	
Alternative	15.76	−0.46	0.81	0.08	3.23	0.00	19.80	−0.38
S AMERICA								
Reference	−27.94		0.79		1.07		−26.07	
Alternative	−27.65	0.28	0.81	0.01	1.07	−0.01	−25.78	0.29
ASIA								
Reference	128.10		9.12		23.16		160.39	
Alternative	127.12	−0.98	9.92	0.79	25.20	2.04	162.24	1.85
OCEANIA								
Reference	3.13		0.10		0.33		3.56	
Alternative	3.13	0.00	0.11	0.02	0.33	0.00	3.58	0.02
EUROPE								
Reference	31.28		4.36		2.95		38.59	
Alternative	31.12	−0.16	4.54	0.19	3.21	0.25	38.87	0.28
WORLD								
Reference	143.25		15.35		31.70		190.30	
Alternative	142.19	−1.06	16.44	1.09	33.99	2.30	192.63	2.32

[1] The assumed elasticity of forest area with respect to price was 0.05, suggesting that a 1% change in timber price would lead to a 0.05% change in forest area. The price effect on forest land use was modeled for both the reference and alternative scenarios.

dampened to a limited degree by wood decay under some conditions in SWDS that results in uncaptured methane emissions. The displacement factor will likely be an underestimate to the extent that the analysis did not include the effect of higher timber prices on forest area. The effect of timber price increase on forest area and the global displacement factor are discussed below.

Third, our estimated global net carbon emissions reduction considers potential leakage effects across countries and world regions brought about by price-induced changes in timber harvests, forest growth and inventory, and production, consumption and net trade of manufactured wood products. Our results indicate that such potential leakage effects could be large for countries that increase their wood product outputs to meet global import demand and that are relatively less affected by SLR and therefore build fewer new housing units. For example, except for Asia, where wood use in new residential units was more than elsewhere, the model outcomes indicate reduced forest sector carbon, suggesting that the projected biomass re-growth, increases in HWP carbon, and avoided emissions were not enough to offset the projected decline in forest biomass carbon in those regions, because those countries increased harvests to supply industrial roundwood or primary wood products to mainly Asia.

Our estimated carbon impacts of increased wood use in SLR-related new residential units suggest some important implications for regional and global forest-based climate change mitigation strategies. First, changes in forest biomass carbon in a country and region are influenced by complex interactions in national and regional forest product markets and forest resources, as wood demand for SLR-related construction increases in other regions (mostly in Asia). These complex interactions suggest that forest sector carbon mitigation impacts of SLR in a country cannot be evaluated in isolation, i.e., without considering the potential effects in other countries/regions; an increase in carbon in one country or a region may be accompanied by decreased carbon in another country or region. Second, the results suggest that fostering wood use in residential construction, especially in those countries where current wood use in construction is small, may be an effective strategy for mitigating the carbon emissions responsible for climate change (e.g., see Amiri et al., 2020; Nepal et al., 2016). This is because increased wood use not only contributes to reducing manufacturing emissions associated with non-wood materials but can also lead to increases in prices, outputs, and revenues (economic incentives to timber producers (forest landowners) and wood products manufacturers), which can spur investment in forest plantations or silvicultural activities leading to increased forest growth and inventory (and forest carbon) (e.g., see Nepal et al., 2016; Miner et al., 2014).

We provided further insights into the magnitudes of price-induced indirect effects on total forest area and hence on forest stock and forest biomass carbon. We modeled such effects by revising our reference and alternative scenarios, where total forest area in individual countries responded to a projected increase in industrial roundwood (IRW) price. Responses were based on an estimated elasticity of forest area with respect to timber price offered by Hardie et al. (2000) for the U.S. South, which showed that forest area increases by 0.2 % for every 1 % increase in timber price. We used a smaller price response on change in forest area globally than the response estimated by Hardie et al. (2000) for the U.S. South. For each country we used a 0.05 % change in forest area for every 1 % change in timber price. Using this factor in both the reference and alternative scenarios, global forest area would increase by 4.8 million ha by 2050, and forest stocks would be about 0.82 billion m^3 higher, relative to the scenarios that did not consider the effect of a price rise on forest area. Increased forest area results in increases in forest biomass carbon stock of 1.81 billion tCO_2e, giving rise to a total net carbon balance of 2.32 billion tCO_2e and a global emission displacement factor of 2.13 tCO_2e per tCO_2e of extra wood used in new residential housing over the next 30 years (Table 8). This result suggests that the overall carbon impacts of increasing wood use in construction is highly dependent on how forest land use and/or forest management activities change in response to higher demand for wood in the construction sector. There is high uncertainty about how much forest area would change with changes in timber prices in individual countries; such responses may be limited by biophysical, economic, and policy variables not modeled in this study. Hence, the projected outcomes suggest the magnitude of the possible market-induced effect on forest land use and on forest sector carbon.

Additionally, our results should be interpreted with caution, given other inherent uncertainties and limitations of our models. First, our results are contingent upon the projected population under risk of permanent exposure and increasing coastal flooding due to SLR over the next 30 years. To the extent that these projections are uncertain, our results are uncertain as well. We also note, as a word of caution, that the localized effects on the socio-economy and ecosystems due to local SLR can be very different (and likely more negative with respect to forest area loss and carbon storage) compared to more aggregate level impacts evaluated in this study based on global mean SLR projections. However, natural forest loss along coastal regions may encourage new forest or retention of forest as the most profitable land use in other parts of the world. Uncertainty in our results may also have been introduced from the specified model parameters in the global forest product market model (e.g., parameters measuring the sensitivity of supply and demand to prices). These parameters, which are based on historical market behavior, may change in the future, with structural changes in the global economy. Therefore, our projected forest products market outcomes are uncertain to the extent that future world market responses differ from our model. Similarly, our estimated wood for non-wood construction product substitution effects are averages based on a review by Sathre and O'Connor (2010), who document that rates of substitution vary substantially across studies. Another limitation of our analysis is that we were able to incorporate only the supply side effects of losses in mangrove forests areas. However, SLR can also affect timber supply resulting from losses of other forests adjacent to coasts because of increasing salinization and storm surges, further shrinking the area of available forest for harvests in the long run.

We also acknowledge that inland relocation of the SLR-affected population is likely to bring about pressure on existing forests and may lead to deforestation or could lead to encroachment of productive agricultural land, especially in countries with weak natural resources governance. However, such potential negative outcomes may be alleviated with managed relocation with careful planning and stringent policies that restrict deforestation or require reforestation to replace forestland cleared for development or utilize less productive (abandoned) agricultural lands for development. Another caveat is that the projected population at risk of SLR, which we used to develop our alternative scenario, ignores currently existing coastal defense mechanisms (such as levees and seawalls) and additional adaptation measures likely to be taken in the future against SLR, which could lessen the SLR threat and thus could lower the number of people affected and the number of new houses needed to be built. Although the building of such a coastal defense infrastructure would involve additional short-run emissions, the overall carbon impacts of such actions are not included in our analysis. Finally, the influence of elevated CO_2 on forest growth is not considered, nor are other effects on forests linked to climate change, such as altered rates of disturbances from insects, disease, wildfire, and hurricanes, although linkages to the SLR-related damages are in need of further study. Despite these limitations and uncertainties, this study provides insights on the direction and magnitudes of likely impacts of an SLR-related shift in the demand for wood products and the associated impacts on forest sector carbon, which should be useful for broader policy purposes.

Author Contributions

Conceptualization, P.N. and J.P.P.; Formal analysis, P.N., J.P.P., L.A. J, and K.E.S.; Funding acquisition, J.P.P.; Investigation, P.N., J.P.P., L.A.

J, and K.E.S.; Methodology, P.N., J.P.P., L.A.J, and K.E.S.; Writing—original draft, P.N.; Writing—review and editing, P.N., J.P.P., L.A. J, and K.E.S.; Visualization, P.N.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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