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Projected effects of the Russian invasion of Ukraine on global forest products markets

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ABSTRACT

This study provided an insight into the projected short-term (<10 years) and long-term (next 10 to 30 years) effects of the ongoing Russian invasion of Ukraine on global forest products trade and associated markets. The assessment was conducted by comparing the projected outcomes from the Global Forest Products Market (GFPM) model for a business-as-usual reference (no invasion) scenario and an alternate scenario representing the current trade sanctions for Russian wood products trade by several major partner countries, and the potential trade disruption in Ukraine due to their military operations, during the 2021–2025 period, and no such trade restrictions thereafter assuming the Russian invasion ends by that time. Results indicate a considerable projected short-term disruption in the Russian, Ukrainian, and the global wood products sector in terms of higher prices of industrial roundwood and finished wood products (up to 3%) and altered production, consumption and trade displacement for wood products. However, in the long run, a lower overall disruption is projected as Russian markets for industrial roundwood and sawnwood start to recover and the global markets begin to converge to pre-invasion levels. The analysis also projects that Russian markets for wood-based panels and paper and paperboard and Ukrainian markets for paper and paperboard do not recover within the next 30 years, suggesting a likely permanent structural change in markets of these wood product groups. These findings suggest several economic and environmental implications for the forest products sector in Russia, Ukraine and the rest of the world in the near- and long-term.

1. Introduction

War has been stated to be the opposite of development (Collier et al., 2003). The consequences of war can be devastating to a nation, ranging from the loss of human lives and properties to undermining economic growth (Karam and Zaki, 2016). Economically, history has shown that war causes significant and persistent economic losses through trade destruction (Glick and Taylor, 2010). Additionally, all forms of armed conflicts may carry the potential to impede international trade (Karam and Zaki, 2016).

On February 24, 2022, Russia invaded the Ukraine. Shortly following Russian invasion, several countries and corporations began imposing economic sanctions against Russia, with the goal of damaging Russian ability and economic potential to finance its war efforts. Some of these sanctions included freezing assets of Russian central bank, and implementing import and export bans on products such as technological inputs, oil, gas, coal, diamonds, and forest products. In terms of forest products, Russia is a major global producer, consumer, and exporter. In 2020, Russia accounted for about 10% each of global production of industrial roundwood and sawnwood (FAOSTAT, 2024a), and 11% and 22%, respectively, of the total world import demand (FAOSTAT, 2024a).

In July of 2022, many countries, such as those in the European Union (EU) and the United Kingdom (UK) instated a complete ban on Russian timber imports. After the ban Russian timber became considered “conflict timber”, which carries restrictions on certification schemes as well as on trade (Hellweger, 2023). In addition to product bans, organizations like the European Pellet Council (EPC), Forest Stewardship Council (FSC), and the Programme for the Endorsement of Forest Certification (PEFC) have responded to Russia’s invasion by suspending all forest and forest product certification schemes in Russia and Belarus (EnPlus, 2022; FSC, 2022; PEFC, 2022). With the significance of Russia to the global timber market, these bans and suspensions have already hampered Russia’s supply of wood to the global market (FAOSTAT, 2024a), and may potentially disrupt the future global forest products

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trade and supply chains.

Prior studies that have evaluated the impacts of war on trade are limited and find varying results. For example, (Pollins, 1989a, 1989b) utilized a public choice model to evaluate the connections between international politics and trade, and concluded that conflicts have a negative impact on trade. Anderton and Carter (2001) also found that major power war induces a decline in trade, relative to pre- and post-war periods, for both major and non-major power dyads, using an interrupted time-series model. Similarly, Keshk et al. (2004)) utilized a simultaneous model of trade and conflict with Militarized Interstate Dispute (MID) data and concluded that conflict hinders trade substantially.

Likewise, Blomberg and Hess (2006); Glick and Taylor (2010); and Karam and Zaki (2016) implemented some forms of the gravity trade model to study the effects of war on trade, and all drew similar conclusions. When terrorism along with internal and external conflict is present, Blomberg and Hess (2006) estimated that the cost of a country's trade loss could be as high as 30% tariff measures. Using data extending back to 1870, Glick and Taylor (2010) evaluated the lagged effects of war on trade and found significantly large and persistent negative impacts on trade, and estimated that costs of lost trade may be as large as the loss of human capital. In the Middle East and North African region, Karam and Zaki (2016) assessed the impacts of various conflict types on trade volume from 1960 to 2013, and found that war generally had significant and negative impacts on trade, and estimated that the average cost of trade resulting from conflict is equal to a tariff of 5% of the trade value.

Contrary to the study results that found that war negatively impacts trade, some studies have found less supporting evidence of this effect. For example, Morrow et al. (1998) and Mansfield and Pevehouse (2000) found that effects of international conflict on trade were inconclusive. Similarly, in the context of non-major world powers, Barbieri and Levy (1999) also found insignificant effects of war on trade.

Recently, the impact on trade of Russian invasion of Ukraine has captured the attention of some researchers. Thus far, several studies have reported significant global impacts on agricultural trade and food security. In the first year of the invasion, Rose et al. (2023) showed that the economic loss of grain export disruptions resulting from the invasion induced negative impacts all across the world (Rose et al., 2023). In terms of wheat, Devadoss and Ridley (2024) found that Russian invasion of Ukraine has caused wheat supply and export disruption, as well as increased wheat prices in other nations, leading to decreased wheat consumptions and increasing threats to global food security. Russia, however, was found to have benefited by exporting wheat at the expense of Ukraine (Devadoss and Ridley, 2024). In terms of external food supply, Russian invasion of Ukraine was found to affect the external food supplies of 279 countries and territories, and 24 of these countries were found to have extreme food supply vulnerability due to a dependence on food imports from Russia and Ukraine (Zhang et al., 2023).

As one of the dominant players in the global wood product markets, restrictions on Russian wood products may have short and long-term implications for the global supply and trade of forest products. For example, global timber prices may increase due to a decrease in supply of Russian timber in the global markets. This may lead importers to find alternative timber and wood products sources to meet their domestic demand. This may come in the form of creating new trade relations with other nations or increasing domestic timber production.

The objective of this study is to understand the near- and long-term effects of the ongoing Russian invasion of Ukraine on the global forest products markets. We compare the projected outcomes from the Global Forest Products Market (GFPM) model simulations for a reference (no invasion) scenario with an alternate scenario, where trade flows of all wood products were restricted from and to Russia as well as Ukraine by a varying degree of magnitudes (33% to 95%) between 2021 and 2025. The alternate scenario represents current and potential trade sanctions for Russian wood products by several major partner countries, and potential trade disruptions in Ukraine due to their active engagement in military operations. Such trade restrictions were then relaxed after 2025 assuming the invasion ends, and trade ban is lifted by then. The results of this analysis provide nuanced perspectives to forest managers, supply chain businesses, and policy makers as they try to plan for a sustainable future for the global forest management and the vibrant forest products supply chain to meet the global demand of wood-based products.

2. Methods

2.1. Theory

Consistent with economics theories and GFPM structure, this study assumed competitive global markets in the forest sector, where market clearing price and quantities of wood products produced, consumed and traded are the ones which maximize the sum of the consumers' and producers' surplus for all products and countries (Buongiorno, 2015; Buongiorno and Johnston, 2018a). Under these assumptions, Fig. 1, a standard partial equilibrium framework, shows how a trade restriction in Russia would affect the market equilibrium price and quantity in the rest of the world. With the trade restriction i.e. import ban from Russia, the export supply curve of the wood product trade shifts left from Export Supply (1) to Export Supply (2), which results in a higher equilibrium price in the export market. The higher price in the export market would lead to higher supply in the rest of the world. The market phenomenon is consistent with trade theory and has been applied to various trade related studies in forest economics (Zhang, 2001; Parajuli and Zhang, 2016; van Kooten and Johnston, 2014; Johnston and Parajuli, 2017).

There are two main approaches to evaluate the likely effects of trade restrictions in the forest sector. The first approach is comparative statics – the comparison of two different economic outcomes, before and after a change in some underlying exogenous variable (e.g., demand or trade shift). It is the analysis of how equilibrium prices and quantities change when other exogenous variables change, and are typically done for one single point in time. Several past studies used this approach using GFPM and other models in the context of evaluating the forest sector impacts of trade constraints (e.g., Buongiorno and Johnston, 2018a; Buongiorno et al., 2017; Buongiorno and Zhu, 2017; van Kooten and Johnston, 2014)). However, this approach ignores the process of adjustment from the old equilibrium to the new one or it neglects the length of time involved in the adjustment process from one to another equilibrium. Thus, a comparative statics analysis is unable to inform how markets evolve over time after the restriction is relaxed. An alternative approach is to carry out scenario projections comparing the BAU and alternate scenarios, which are widely used in economics literature to understand market recovery path after a shock. Here, model outcomes for future years with specific demand or supply shock is compared with those without a shock. In the forest sector, such an approach has been widely used to understand the longer-term effect on wood products markets of demand and supply shocks and to understand how the market evolves over time (e.g. Buongiorno et al., 2011, 2014; Johnston, 2016; Li et al., 2008; Nepal et al., 2019a, 2022). In this study, we followed the projection approach. First, we constrained the model to partially restrict trade for Russia and Ukraine in 2025. Then, after 2025, we relaxed the trade constraints and ran the model through 2050 to observe how global and regional markets would evolve post trade relaxation. One key limitation of a dynamic projection approach is that it assumes same market structures represented by historical relationships between market drivers and forest sector variables. For example, it is assumed that an increase in income per capita will lead to the same change in demand for wood products, as estimated based on historical relationship of income and wood products demand. However, such relationships may change in future, leading to different outcomes than represented by historical market conditions, thus adding uncertainty to the projected outcomes.

The simulated effect on the global forest products production, consumption and trade of such trade restriction in 2025 and then relaxation

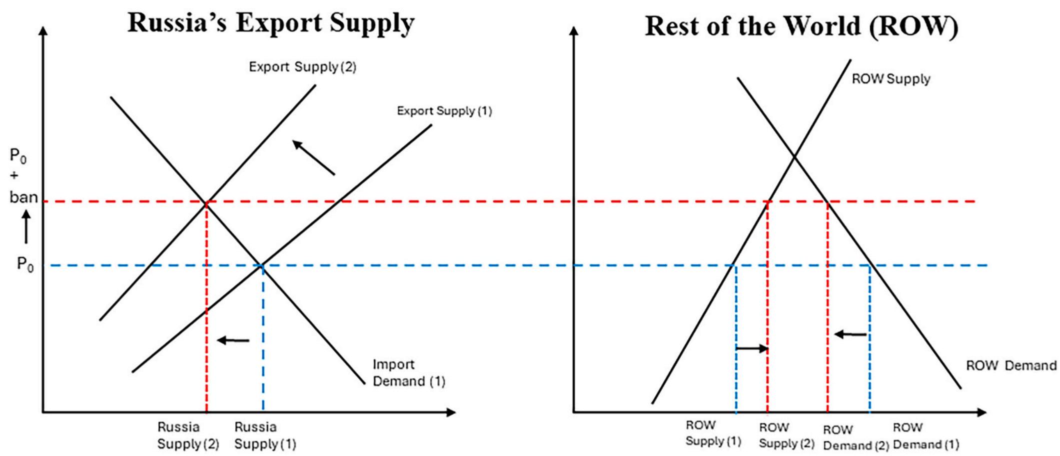

Fig. 1. Effect of an import ban of Russian wood products on the price and quantity in the rest of the world.

of trade restriction thereafter are evaluated using the latest publicly available version of the Global Forest Products Model (GFPM, (Buongiorno, 2015; Buongiorno et al., 2003; Nepal et al., 2021), with the base year 2020. The most recent version of the complete GFPM software, the data, and the user and calibration guides are described in Buongiorno and Zhu (Buongiorno and Zhu, 2023a, 2023b) and are freely available for academic research at https://buongiorno.russell.wisc.edu/gfpm/. GFPM has been successfully utilized to evaluate the effects of varying trade policies on the global wood products trade, their production, and prices. For example, Buongiorno and Johnston (2018a), used the GFPM to estimate the potential impact of prohibitive import barriers in the United States and of countervailing measures abroad on the economic welfare of consumers and producers in the forest sectors of the United States and of other countries. Likewise, Buongiorno et al. (2017) is another example of GFPM application to assess the gains and losses in the forest sector resulting from international trade as compared to Autarky. GFPM was also applied to forecast the effects of Brexit on the global forest products industry (Johnston and Buongiorno, 2017).

GFPM is a dynamic recursive partial market equilibrium model of the global forests and the wood products sector. GFPM models production, consumption, trade, and prices of 14 categories of forest products in 180 countries and territories (Buongiorno, 2015; Buongiorno et al., 2003). The included forest products represent five types of raw materials (industrial roundwood, roundwood, fuelwood, recovered paper, and other fiber pulp), two intermediate products (mechanical and chemical pulp) and nine end products (sawnwood, plywood, particleboard, fiberboard, newsprint, printing & writing paper, other paper, fuelwood, and other industrial roundwood). For each period and each product, GFPM provides the market equilibrium solution of quantity produced, consumed, and traded along with their prices. It models the demand for end products and supply of roundwood feedstock. The demands for end products are modeled as functions of exogenously projected per capita gross domestic product (GDP) and their endogenously projected prices. The supply of raw materials (roundwood) is modeled as a function of the forest stock and their endogenously projected prices. Forest stock is estimated as last year's forest stock plus the current year's growth minus the current year's harvest. Forest stock growth (net of mortality) before harvest is modeled as a negative nonlinear function of forest stock density (i.e., forest stock per unit of forest area) (Turner et al., 2006). Changes in forest area in individual countries is modeled based on the environmental Kuznets curve (Koop and Tole, 1999; Nepal et al., 2019b; Turner et al., 2006), which is a quadratic function of per capita GDP, suggesting that forest area change is negative at low GDP per capita, positive and increasing at higher GDP per capita, and decreasing and approaching zero forest area change at very high GDP per capita. Consumption of raw materials (e.g., industrial roundwood) is derived from the demand for end products through i) the input–output coefficients which is a ratio of the quantity of industrial roundwood input used in manufacturing a product to the quantity of that product, and ii) manufacturing costs (labor, capital, energy).

The standard GFPM model does not represent bilateral trade flows. Instead, trade is modeled to occur from a country to the rest of the world, and from the rest of the world to a specific country. Trade is driven by the economic growth of the countries and by their relative competitive advantage. The equilibrium quantities of production, consumption, trade and prices in each country and each year is found by maximizing the quasi welfare of the world forest sector: the value of the products to consumers, minus their cost of production and transport (see eq. 1 in Appendix A). Equilibrium prices are the shadow prices of the material balance constraints in each country, such that, for each product and country, demand equals domestic production plus imports minus exports (see eq. 5 in Appendix A). While it is technically possible to modify the model to represent bilateral trade flows with those countries that have not banned trade with Russia, this is difficult to model due to a lack of available bilateral trade flow data and time and resources needed to develop a fully functional bilateral trade model. We chose to use the standard version of GFPM since our focus was to understand the implications of the Russian invasion of Ukraine on global forest products markets, rather than on their specific trade partner countries, for which the standard model is more suitable. Note that GFPM does not consider the exchange rate as a driver for trade projections. The impacts of exchange rates on international forest products trade are widely debated, and the empirical evidence regarding this issue is still inconclusive (Bolkesjø and Buongiorno, 2006).

A detailed description of the model structure and its mathematical formulations are available in several past publications (e.g., see Buongiorno, 2015; Buongiorno et al., 2003; Buongiorno and Zhu, 2023a, 2023b; Nepal et al., 2021). We briefly describe the key equations and parameters used in GFPM BAU model in Appendix A for readers' quick reference.

2.2. Scenarios

Two scenarios were developed. First, the reference scenario represented the business-as-usual (BAU) case, where the projected forest products markets outcomes were driven by the GFPM's baseline parameters and variables (see eqs. 1 to 17 in Appendix A). Thus, the BAU model outcomes represented continuation of BAU market trends, policy, economy, demography, and technology. The BAU model, which was calibrated for base year 2020, provided solutions that closely replicated the observations for the base year on production, consumption, price, and net trade of wood products. The BAU model solutions for the future years were driven by specified demand, supply, manufacturing, and trade parameters (eqs. 1 to 17 in Appendix A) accompanied by specified growth rate of exogenous demand shifter (GDP), endogenous supply shifter (forest stock), and exogenous technology shifters (input/output coefficient and manufacturing costs). The baseline GFPM used GDP and GDP per capita growth as projected in scenario B2 used in the 4th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) and US Forest Service's 2010 Resource Planning Act Assessment (USDA Forest Service, 2012). In the alternate scenario, the same BAU model was used, but with only one modification. The modification was done to constrain (reduce) forest products trade in Russia and Ukraine for the period 2025 by varying order of magnitudes. All other parameters and variables remained same as in the BAU scenario, except for the trade constrained for Russia and Ukraine in 2025. Thus, the difference in model solutions between the BAU and alternate model runs could be attributable to the trade restriction in Russia and Ukraine in 2025 and unconstrained trade after 2025.

The reason for such trade reductions in the alternate scenario is twofold: 1) ongoing trade ban from the partner countries, and 2) reduced forest production activities due to military operations. In the alternate scenario, trade flows in Russia were exogenously shifted downward by 33% to 95% during the 2021–2025 period. The selected amount of trade reductions in this period is based on the average share of Russian wood products export to China and India and the rest of the world. While Russia is facing trade sanctions from most of its trade partners, China and India have not announced any ban for Russian goods and services and continued to trade with Russia, and recent trends show that Russian wood imports in China and India increased considerably (Global Wood, 2023; Trading Economics, 2024). The most recent available historical data (2015 to 2017) from the FAOSTAT bilateral trade flow database (FAOSTAT, 2024b) indicated that China shared, on average, about 60% and 40% of total Russian industrial roundwood and sawnwood export markets, respectively (Table 1a), while India had a negligible share for these products, suggesting that the rest of the world had 40% and 60% of share, respectively. Similarly, China's and India's combined shares of wood pulp, paper and paperboard, and wood-based panels were 67%, 20%, and 5%, respectively. Therefore, our alternate scenario assumed trade flows from Russia were restricted by 33% (wood pulp), 40% (industrial roundwood), 60% (sawnwood), 80% (paper and paperboard), and 95% (wood-based panels) during the 2021 to 2025 period (Table 1a and 1b). While there is no official sanction for Ukrainian wood products, its trade flows were assumed to be reduced by 50% for the same period. We considered the arbitrary 50% reduction in trade just to capture the potential disruption in its wood products market due to active military operations. Notably, Ukraine has a tiny share in global wood products trade for all wood products, except for sawnwood, for which it had 2% share in 2020 (FAOSTAT, 2024a). Therefore, it is expected that the global and regional market outcomes of trade restriction in Ukraine would be small, regardless of the percentage in trade restriction modeled.

Table 1a
Average historical (2015 to 2017) Russian total export of wood products and their share by China and India (Source: FAOSTAT Trade Flows Database (FAOSTAT, 2024b).

Reporting country	Russia's total exports	Trading partner's share		
		China	India	Combined
Industrial roundwood	19.63 million m^3	60%	<0.01%	60%
Sawnwood	27.02 million m^3	39%	<0.05%	40%
Wood-based panels	4.77 million m^3	4%	0.11%	5%
Wood pulp	2.26 million ton	65%	2%	67%
Paper and paperboard	2.9 million ton	14%	6%	20%

Table 1b
Trade quantities projected in 2025 in the BAU scenario, and target reduction (%) and achieved reductions in trade quantities in the trade constrained scenario.

Country	Commodity	GFPM projected trade quantities in 2025 (BAU scenario)		Target reduction constraint (%)	GFPM-projected trade quantity in 2025 after constraint applied (invasion scenario)	
		Export	Import	%	Export	Import
Russia	Industrial roundwood	26,193	8*	40%	15,766	0
	Sawnwood	31,729	35*	60%	12,751	0
	Wood-based panels	5,684	671*	95%	288	0
	Wood pulp	2,438	163*	33%	1,632	0
	Paper and paperboard	2,980	833*	80%	610	0
Ukraine	Industrial roundwood	623	17*	50%	313	0
	Sawnwood	3,480	22*	50%	1,742	0
	Wood-based panels	574	729	50%	286	363
	Wood pulp	0	68*	50%	0	3
	Paper and paperboard	125*	617	50%	0	268

* Model was unable to achieve target reductions in imports for these products. However, this is a non-issue as import values for these products for Russia and Ukraine are too small to influence the model outcomes.

2.3. Scenario implementation in GFPM

We constrained the trade in Russia and Ukraine in the standard GFPM base model by introducing an exogenous trade shifter and iteratively changing an annual growth rate of this shifter until target reductions in the trade quantities (Table 1b) are achieved in 2025. In GFPM, projections from the base year (2020) to future years are provided at 5-year intervals through calculation of the changes in the condition of the global equilibrium from one period to the next. Such constraints were then removed for the subsequent periods (after 2025 to 2050), allowing the model to endogenously solve trade thereafter, assuming that Russian invasion of Ukraine will end in 2025 and that trade sanctions will be lifted. In other words, all parameters of the model remained the same as BAU reference scenarios after 2025. The projected differences in model outcomes between the BAU reference and the alternate scenarios allowed us to understand the likely effects of the Russian invasion of Ukraine on global wood products markets. The model was run through 2050, allowing us to understand both the likely near-term and long-term effects.

3. Results

In what follows, we describe first the projected outcomes for Russia and Ukraine, followed by the description of the associated effects at the global, regional, and selected country levels.

3.1. Effects on the Russian and the Ukrainian wood products markets

The restricted trade from Russia and Ukraine to and from the rest of the world during the 2021–2025 period was shown to render substantial disruptions or likely permanent structural changes in the Russian and Ukrainian wood products markets. While their wood products markets were shown to generally follow a V-shaped recovery after 2025 (after which the scenario assumed that the invasion would end, and the trade ban would be lifted); the recovery took at least two decades to reach the BAU levels (without invasion) for most of the products. However, the production and trade of wood-based panels and paper and paperboard products were found to never reach to the BAU projected levels throughout the projection period, indicating a likely permanent structural change for these products in Russia and Ukraine.

The Russian wood products market was projected to suffer due to its invasion of Ukraine at least for the next two decades, after which it was shown to recover its production, consumption, and trade of most of the products to BAU projected levels (Fig. 2). For example, the Russian production and export of industrial roundwood was projected to reach the BAU levels only after 2045, while its consumption was shown to reach the BAU level a little sooner (after 2040). Similarly, the Russian sawnwood production and export were shown to reach the BAU levels after 2040 with a negligible effect on its consumption. Likewise, wood pulp, which had only 33% of trade restricted during the 2021–2025 period, was shown to reach the BAU level after 2035 and then to surpass the projected BAU level production and export after 2035. In contrast, wood-based panels and total paper and paperboard, for which Russian export was restricted by 95% and 80% from 2021 to 2025, respectively, did not reach to the BAU level production and export, indicating a likely permanent structural change in markets of these two groups of wood products.

The effect on the industrial roundwood market is the result of restricted trade of industrial roundwood itself and manufactured products such as sawnwood and wood-based panels, for which industrial roundwood is used as a feedstock. Accordingly, the trade restriction resulted in a projected decrease in Russia's industrial roundwood production by 70.5 million cubic meters (m^3) in 2025, 60 million m^3 in 2030 and only 5 million m^3 in 2050, representing reductions of 37%, 30% and 2% in the production compared to the projected BAU levels in those years, respectively (Table 2). Russia's industrial roundwood consumption also declined proportionately since it couldn't use industrial roundwood (feedstock) to produce and ship sawnwood and other finished products to meet the BAU level global import demand for these products, although industrial roundwood consumption was projected to rebound to the BAU level in 2045 (Table 2). Its industrial roundwood export was projected to decline by 10.4, 13.9, and 4.7 million m^3 in 2025, 2030, and 2050, representing 40%, 40% and 11% lower export than the projected BAU scenarios in those years, respectively (Table 2).

A 60% decline in Russia's sawnwood export market during 2021–2025 period was shown to result in about 19 and 14 million m^3

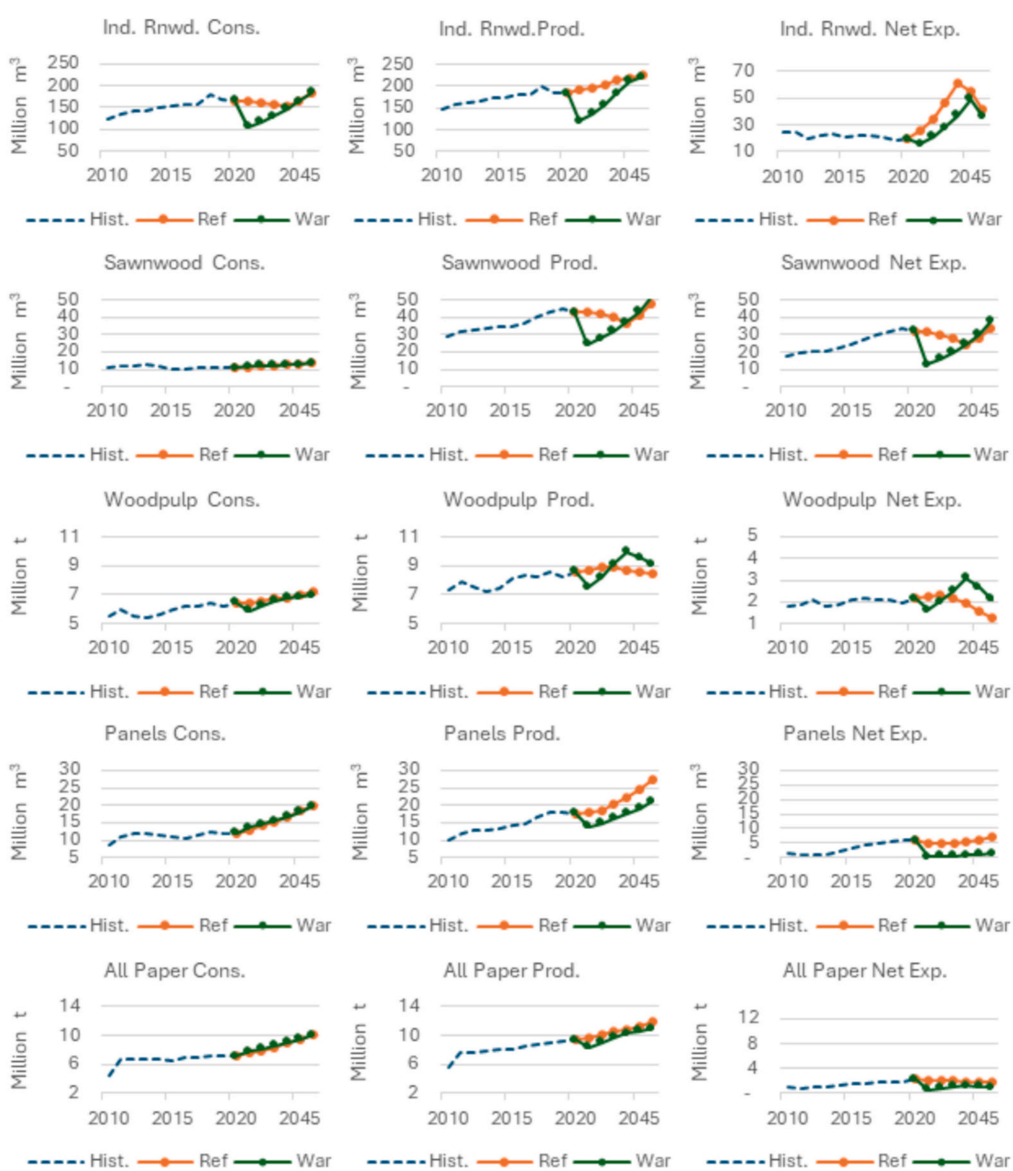

Fig. 2. Projected consumption, production, and export of wood products for Russia in the business-as-usual reference and the trade constrained scenarios, 2020–2050.

Table 2
Base year values and projected changes in consumption, production and net export (thousand cubic meters) of industrial roundwood between the reference and the trade constrained scenarios by world regions and selected countries, 2025, 2030, and 2050.

Region / Country	Consumption				Production				Net Export			
	Observed	Difference from Ref			Observed	Difference from Ref			Observed	Difference from Ref		
	2020	2025	2030	2050	2020	2025	2030	2050	2020	2025	2030	2050
Africa	**38,797**	**303**	**209**	**91**	**44,033**	**624**	**673**	**739**	**5,235**	**321**	**464**	**648**
Gabon	2,644	117	66	9	2,659	116	64	3	15	2	2	6
South Africa	13,121	45	263	683	15,039	45	263	683	1,918	0	0	0
N America	**503,453**	**10,846**	**7,760**	**−1,632**	**515,962**	**12,423**	**9,989**	**−5,940**	**12,509**	**1,577**	**2,229**	**−4,308**
USA	353,974	7,342	7,266	3,732	366,408	7,342	7,266	5,482	12,434	0	0	9,214
Canada	138,743	3,142	221	5,336	138,669	4,709	2,453	448	74	1,567	2,233	4,888
S America	**203,166**	**3,866**	**1,886**	**−1,054**	**216,320**	**5,178**	**3,581**	**−701**	**13,154**	**1,312**	**1,695**	**352**
Argentina	12,901	311	200	78	13,362	311	200	127	461	0	0	49
Brazil	130,713	1,980	553	430	134,168	3,251	2,210	64	3,455	1,271	1,657	494
Chile	38,659	1,429	1,005	640	43,893	1,429	1,004	679	5,234	1	1	40
Colombia	1,161	36	31	22	1,265	35	30	16	104	0	0	6
Asia	531,400	9,791	11,867	10,564	445,954	11,023	7,107	1,052	85,446	1,232	4,760	11,616
China	283,714	4,419	7,551	8,833	206,560	4,418	2,132	740	77,154	1	5,419	9,573
India	53,095	791	610	329	49,136	791	610	330	3,959	0	0	0
Indonesia	61,120	1,030	772	349	61,170	1,613	1,203	472	50	583	431	122
Japan	41,755	1,957	1,684	929	21,204	719	469	239	20,551	1,237	1,216	1,168
Malaysia	12,347	314	31	429	13,715	562	401	75	1,368	248	432	355
Oceania	28,627	622	525	84	72,356	2,635	1,852	282	43,729	2,013	1,327	198
Australia	13,423	434	423	22	29,028	1,158	811	297	15,605	724	388	320
New Zealand	13,502	182	102	120	35,969	1,184	843	99	22,467	1,002	740	219
Europe	**589,874**	**−53,858**	**−51,577**	**−25,901**	**607,309**	**−60,313**	**−52,532**	**−10,780**	**17,436**	**−6,455**	**−955**	**15,121**
E. Union	**390,956**	**6,469**	**−5,428**	**−27,012**	**384,686**	**10,803**	**7,970**	**−4,854**	**−6,270**	**4,334**	**13,398**	**22,158**
Austria	24,590	1,503	1,525	2,662	12,769	427	229	176	11,821	1,076	1,296	2,837
Czech Rep.	10,605	443	342	488	26,520	444	342	488	15,915	1	1	0
Finland	64,239	1,332	1,510	7,091	54,883	1,331	978	561	9,356	0	2,488	6,531
Germany	51,117	3,643	3,072	606	57,151	2,232	1,434	1,094	6,034	1,412	1,638	488
Italy	8,746	1,563	3,395	4,097	5,080	142	73	206	3,666	1,705	3,468	4,303
Poland	36,795	1,625	2,326	4,452	36,858	1,111	1,021	1,803	62	2,736	3,347	2,649
Spain	12,828	269	397	325	14,060	269	397	325	1,232	0	0	0
Sweden	76,623	1,884	1,837	7,070	68,699	1,883	1,140	554	7,923	0	2,976	6,517
UK	8,646	367	299	39	7,867	367	299	38	779	0	0	0
Russia	164,997	60,102	46,107	364	184,675	70,521	59,972	5,021	19,678	10,419	13,865	4,656
Ukraine	6,506	1,658	1,214	862	6,953	1,951	1,612	424	447	293	398	1,285
World	**1,895,317**	**−28,431**	**−29,330**	**−18,014**	**1,901,935**	**−28,430**	**−29,329**	**−18,015**	**6,617**	**0**	**0**	**0**

less sawnwood production and export from Russia in 2025, and 2030, respectively (Table 3), representing 43% and 33% declines in production and 60% and 48% declines in export compared to the BAU level production and export for those years, respectively. It was, however, projected that sawnwood production and export would be expanded by about 3.6 million m^3 (11% higher trade) in 2050, compared to the BAU level.

In contrast, a 95% restriction in Russia's wood-based panels export in 2025 and lifting of such a restriction thereafter was shown to result in lower production and net trade in the alternate scenario throughout the projection period, with a projected gap of about 6 million m^3 by 2050 (Table 4). Similar outcomes were projected in case of paper and paperboard, but with a smaller projected gap of about 1 million metric ton by 2050 (Table 5).

The Russian market for wood pulp, for which the alternate scenario assumed 33% trade restriction, was projected to recover sooner than industrial roundwood and sawnwood markets, and its production and net trade were shown to expand slightly after 2035, compared to the BAU projected levels (Fig. 1). However, these expansions came at the expense of slight declines in domestic consumption (Table 6).

The Ukrainian wood products markets were also found to realize similar projected trends as in Russia for industrial roundwood and sawnwood markets but with slower recovery paths than in Russia, reaching their BAU projected levels only around 2050 (Fig. 3). Similar to the projected results for Russia, consumption and production of paper and paperboard in Ukraine was also projected to not reach the BAU levels throughout the projection period (Fig. 3), resulting into a projected gap in its production of about 1 million metric ton (mt) by 2050 (Table 5). Ukraine's net trade of total paper and paperboard increased slightly in the alternate scenario (Table 5) because of its reduced imports than in the BAU scenario. However, for wood-based panels, the restricted trade in 2025 resulted in expanded domestic production and net trade than the BAU levels throughout the projection period after 2025, with a projected expansion in its production and net trade of about 1.4 million m^3 by 2050. Ukraine does not produce wood pulp, and the restricted trade resulted in slight reduction in consumption and net trade of wood pulp throughout the projection period.

3.2. Effects on the global, regional, and other countries' wood products markets

The Russian invasion of Ukraine related restricted trade in Russia and Ukraine not only affected their domestic markets significantly but also led to notable effects on wood products markets at global, regional, and individual country levels. For example, restricted trade from Russia and Ukraine led to 2% to 3% increase in global prices of wood products in 2025, respectively, compared to the projected BAU level prices in that year (Fig. 4). The prices then started to decline but remained higher than BAU levels until 2040 before converging to the BAU level prices. These changes in prices altered the profitability of production and trade of various products in individual countries.

While the world consumption (and production) remained unchanged for manufactured wood products, the global industrial roundwood production (consumption) did not reach the BAU level during the projection period. For example, global industrial roundwood production was projected to decline by 28 million m^3 in 2025 and 17 million m^3 in 2050 (Table 2). This outcome is attributed to a shift in production and trade of sawnwood by other countries in the face of restricted trade from

Table 3
Base year values and projected changes in consumption, production and net export (thousand cubic meters) of sawnwood between the reference and the trade constrained scenarios by world regions and selected countries, 2025, 2030, and 2050.

Region / Country	Consumption				Production				Net Export			
	Observed	Difference from Ref			Observed	Difference from Ref			Observed	Difference from Ref		
	2020	2025	2030	2050	2020	2025	2030	2050	2020	2025	2030	2050
Africa	**15,090**	**−30**	**−24**	**−13**	**11,662**	**79**	**−37**	**−370**	**−3,429**	**109**	**−13**	**−357**
Gabon	69	0	0	0	919	5	28	127	850	6	28	127
South Africa	2,241	1	4	9	2,156	1	52	123	85	0	56	132
N America	**124,236**	**−263**	**−207**	**65**	**126,335**	**4,098**	**2,615**	**−2,157**	**2,099**	**4,361**	**2,822**	**−2,222**
USA	101,194	182	165	64	80,695	2,374	2,523	1,412	20,500	2,557	2,687	1,349
Canada	15,303	57	29	1	41,128	1,480	94	3,562	25,825	1,537	66	3,563
S America	**18,559**	**−54**	**−39**	**5**	**26,386**	**443**	**308**	**−604**	**7,827**	**497**	**347**	**−609**
Argentina	3,370	10	6	3	3,750	65	2	151	380	74	4	154
Brazil	6,932	23	16	2	10,240	22	16	1	3,308	0	0	0
Chile	4,745	18	14	5	8,196	322	251	473	3,451	340	265	478
Colombia	353	0	1	0	336	0	0	0	17	0	0	0
Asia	**203,208**	**−608**	**−330**	**−2**	**150,703**	**7,202**	**9,084**	**6,781**	**−52,505**	**7,810**	**9,415**	**6,783**
China	122,100	429	224	12	86,126	4,885	7,248	6,003	35,975	5,315	7,472	5,991
India	25,407	29	13	10	23,975	720	526	134	1,432	748	538	144
Indonesia	2,591	10	8	5	2,645	10	8	5	54	0	0	0
Japan	13,463	45	22	6	8,479	873	701	200	4,984	918	723	194
Malaysia	1,897	7	4	0	2,912	202	14	555	1,015	210	18	554
Oceania	**7,833**	**−27**	**−21**	**−19**	**9,255**	**389**	**381**	**−107**	**1,422**	**416**	**402**	**−89**
Australia	4,853	16	10	2	4,452	268	287	114	401	284	297	116
New Zealand	2,516	9	9	21	4,313	122	95	4	1,797	131	104	25
Europe	**116,472**	**212**	**190**	**−325**	**170,553**	**−12,980**	**−12,783**	**−3,831**	**54,081**	**−13,192**	**−12,973**	**−3,506**
E. Union	**91,018**	**−262**	**−172**	**−189**	**112,775**	**5,926**	**1,652**	**−7,433**	**21,757**	**6,188**	**1,823**	**−7,244**
Austria	6,420	22	13	1	10,564	1,058	1,184	2,825	4,144	1,080	1,197	2,825
Czech Rep.	2,140	5	6	196	4,867	259	205	111	2,727	264	210	85
Finland	3,370	10	7	0	11,421	690	369	3,042	8,051	700	361	3,042
Germany	20,782	74	38	1	25,746	3,643	3,646	663	4,964	3,717	3,684	664
Italy	5,319	18	9	18	958	561	1,244	1,500	4,361	543	1,235	1,482
Poland	5,055	17	19	25	4,809	571	774	1,509	246	554	754	1,534
Spain	3,701	3	4	2	2,857	3	4	2	844	0	0	0
Sweden	6,277	21	14	1	18,779	975	615	3,282	12,502	996	602	3,283
UK	10,706	35	18	6	3,474	357	309	101	7,233	392	327	95
Russia	10,796	520	386	129	42,786	18,423	13,933	3,521	31,990	18,944	14,319	3,650
Ukraine	63	1	0	0	3,204	1,715	1,669	403	3,141	1,717	1,669	403
World	**485,399**	**−770**	**−431**	**−288**	**494,893**	**−770**	**−431**	**−288**	**9,495**	**0**	**0**	**0**

Russia and Ukraine during 2021 to 2025. The model results suggested that other countries would offset about 44 million m^3 (61%) and 29 million m^3 (53%) of 72 million m^3 and 62 million m^3 of the projected loss in industrial roundwood production by Russia and Ukraine in 2025 and 2030, respectively (Table 2).

Although all major world regions and several other countries expanded their industrial roundwood production and export to compensate for the restricted trade flows from Russia and Ukraine in 2025, they tended to revert to the BAU level production and export, as Russia and Ukraine started to recover their industrial roundwood production and trade in the assumed post-invasion period. For example, while North America (mainly the USA and Canada) expanded its industrial roundwood production by 12.4 million m^3 in 2025, it only increased its production by about 10 million m^3 in 2030 but reduced its production by 6 million m^3 in 2050, compared to the projected BAU levels (Table 2). All other regions except Europe and Africa followed the similar trends with Asia, South America, and Oceania, expanding their industrial roundwood production in 2025 (by 11.0, 5.2, and 2.6 million m^3, respectively) and in 2030 (by 7.1, 3.6, and 1.9 million m^3, respectively), but reducing their industrial roundwood production in 2050 (by 1.1, 0.7 and 0.3 million m^3, respectively). Although Europe offset about 10 million m^3 of total 72 million m^3 of the reduced Russian and Ukrainian industrial roundwood production in 2025, our model projected an overall decline in its production by 9% in 2025, 8% in 2030, and 1% in 2050. The majority of this offset came from the European Union region, which expanded its industrial roundwood production by about 11 million m^3 in 2025 and 8 million m^3 in 2030, but contracted its production in 2050 by about 5 million m^3 (Table 2). In contrast, Africa showed expanded production and export throughout the projection period, albeit by smaller magnitudes (about 1% in production and 5% to 10% in export).

In contrast to the industrial roundwood results, other countries and regions offset almost all the reduced sawnwood production and trade from Russia and Ukraine. For example, to compensate for the projected loss of approximately 20 million m^3 of sawnwood production and export in 2025 from Russia and Ukraine, regions such as Asia and Europe expanded their sawnwood production by 7 million m^3 each, followed by North America (5 million m^3), with the remaining gaps filled by South America, Oceania, and Africa (Table 3). The majority of expanded sawnwood production in Europe came from the European Union region (about 6 million m^3 in 2025 and about 2 million m^3 in 2030). Similarly, to compensate for the projected loss of 4 to 6 million m^3 of wood-based panels trade from Russia during the 2025–2050 period, regions such as South America, Asia, North America, and Africa were projected to expand their wood-based panel production throughout the projection period, with projected production expansion in 2050 of 2.9, 2.7, 1.1, and 0.18 million m^3, respectively above BAU levels (Table 4). Likewise, regions such as Asia, Oceania, North America, and Africa were shown to expand their total paper and paperboard production slightly in the alternate scenario in response to the projected declined production and trade from Russia (Table 5). However, South America, especially Brazil was shown to reduce its wood pulp production by about 1.3 million mt by 2050 in the alternate scenario after Russia recovered its wood pulp market (Table 6). Because all the model parameters and variables were the same between the BAU and invasion scenarios, except for the restricted trade in Russia and Ukraine in 2025 and removed restriction thereafter, the projected forest products market outcomes for individual countries and regions in the invasion scenario can be attributable to

Table 4
Base year values and projected changes in consumption, production and net export (thousand cubic meters) of wood-based panels between the reference and the trade constrained scenarios by world regions and selected countries, 2025, 2030, 2050.

Region / Country	Consumption				Production				Net Export			
	Observed	Difference from Ref			Observed	Difference from Ref			Observed	Difference from Ref		
	2020	2025	2030	2050	2020	2025	2030	2050	2020	2025	2030	2050
Africa	**7,131**	**−20**	**−21**	**−32**	**4,359**	**73**	**83**	**180**	**−2,772**	**93**	**104**	**212**
Gabon	153	1	0	0	453	54	61	126	300	55	61	126
South Africa	1,565	1	4	9	1,538	1	4	9	27	0	0	0
N America	**61,954**	**−275**	**−196**	**50**	**50,505**	**778**	**729**	**1,068**	**−11,449**	**1,053**	**924**	**1,019**
USA	50,810	204	157	51	36,090	882	775	560	14,720	1,086	932	509
Canada	7,095	53	26	0	12,493	106	51	518	5,398	54	25	518
S America	**15,051**	**−73**	**−50**	**−3**	**19,784**	**940**	**1,112**	**2,899**	**4,732**	**1,013**	**1,162**	**2,903**
Argentina	924	4	3	1	983	33	56	143	59	37	59	142
Brazil	9,030	43	30	5	13,410	698	838	2,312	4,380	740	868	2,317
Chile	2,225	16	10	3	3,263	193	204	402	1,038	209	213	399
Colombia	687	4	3	0	232	12	13	19	455	15	16	20
Asia	**234,865**	**−1,362**	**−817**	**215**	**235,990**	**769**	**920**	**2,650**	**1,125**	**2,131**	**1,737**	**2,434**
China	170,336	1,028	613	249	177,251	1,027	613	2,171	6,915	0	0	1,922
India	13,579	23	21	12	12,748	22	20	89	831	1	1	101
Indonesia	3,356	24	12	10	6,755	904	748	486	3,399	929	760	496
Japan	8,531	80	31	6	4,967	400	381	177	3,564	481	413	171
Malaysia	3,283	17	14	4	4,099	25	29	268	816	9	16	272
Oceania	**3,650**	**−24**	**−17**	**−20**	**3,556**	**−26**	**−101**	**−40**	**−94**	**−3**	**−84**	**−20**
Australia	2,440	17	9	2	1,779	5	10	77	661	21	1	80
New Zealand	1,011	6	7	17	1,586	33	91	119	575	27	84	101
Europe	**85,246**	**463**	**226**	**−423**	**91,252**	**−3,823**	**−3,617**	**−6,970**	**6,006**	**−4,286**	**−3,843**	**−6,547**
E. Union	**59,742**	**−296**	**−240**	**−123**	**61,448**	**65**	**−264**	**−2,190**	**1,706**	**361**	**−24**	**−2,068**
Austria	1,547	8	5	1	3,200	139	249	1,212	1,653	131	244	1,212
Czech Rep.	1,072	4	6	190	1,633	0	4	222	561	5	2	32
Finland	638	4	2	0	1,278	160	208	426	640	164	210	426
Germany	12,835	72	52	1	13,013	246	509	1,105	179	174	457	1,103
Italy	6,103	23	13	19	4,138	24	13	19	1,966	0	0	0
Poland	12,038	62	73	92	12,186	62	73	112	147	0	0	204
Spain	3,325	16	11	2	4,112	241	349	366	787	257	360	368
Sweden	1,696	7	5	0	719	6	4	0	977	1	1	0
UK	6,422	49	38	12	3,228	34	31	7	3,194	15	7	5
Russia	11,907	743	459	274	17,652	3,982	3,751	6,081	5,745	4,725	4,210	5,806
Ukraine	3,271	86	59	14	3,265	165	577	1,357	6	78	518	1,371
World	**407,897**	**−1,290**	**−874**	**−213**	**405,445**	**−1,288**	**−873**	**−212**	**−2,452**	**0**	**0**	**0**

increased world prices caused by the restricted trade in Russia and Ukraine. Such price changes in turn altered the competitive advantage of individual countries in producing and exporting products to fulfill gaps in world import demand created by trade disruptions in Russia and Ukraine, as depicted in Fig. 1.

4. Discussion and conclusions

Along with insurmountable casualties and the destruction of physical infrastructure, wars have substantial impacts on international trade, the economic health of countries, and the overall global economic welfare (Glick and Taylor, 2010). As one of the leading producers and exporters of forest products globally (FAOSTAT, 2024a), Russia realized a significant distortion in exporting wood products amid strong trade sanctions from most of the trading partners due to its engagement in the war of aggression with Ukraine since the early 2022. Our study findings offer insights on how such trade sanctions related effects would manifest into Russian, Ukrainian, and the rest of the world's wood products markets over the next three decades. To our knowledge, no previous studies so far have investigated the effects on the global wood products sector of the Russian invasion of Ukraine. Our study fills this gap by providing an insight into not only the potential short-term (<10 years) but also the long-term effects (10 to 30 years) of the Russian invasion of Ukraine on the global wood products sector.

Our analysis suggests a considerable projected short-term disruption in the Russian, Ukrainian, and global wood products sectors but a lower overall disruption in the long-term as the Russian markets for the majority of products starts taking a V-shaped recovery path and the global markets begin to converge to pre-invasion levels in the long-run. However, our projections also indicate that Russian markets for wood-based panels and paper and paperboard do not recover, at least over the next 30 years, indicating a likely permanent structural change for these wood product groups. The potential reason for such outcomes is that we assumed large restrictions in trade for these products such as 95% ban for wood-based panels and 80% restriction for paper and paperboard produced in Russia. To fill this void, as explained by the Heckscher-Ohlin (H—O) trade theory, other countries and regions, especially with better competitive advantage in producing and trading these products (e.g., South America, Asia, North America, and Africa for wood-based panels and Asia, Canada, Oceania, and Africa for paper products) likely find it profitable to continue to expand their production capacity and net exports, displacing a part of the Russian market share for these products.

H—O trade theory suggests that countries produce and export goods that utilize their abundant factors of endowment and import goods that use their relatively scarce factors of endowment (Feenstra and Taylor, 2021). With the removal of Russia from the world market, it makes sense that production and export centers would shift to other countries with abundant feedstocks, labor, and capital for the respective wood products. As wood products production and trade shift to the other nations to fill the Russian trade gap, it is likely that these nations will work to improve their production factors, in turn making them more efficient than Russia even after Russian re-enters the world market.

Despite being a small player in the global wood-product trade, Ukraine is also expected to have substantial impacts on production and trade of most of the wood products. These projected results from the GFPM are in line with the general expectation and other recent literature evaluating the effects of Russian invasion of Ukraine. For example, Rose

Table 5
Base year values and projected changes in consumption, production and net export (thousand metric tons) of total paper and paperboard between the reference and the trade constrained scenarios by world regions and selected countries, 2025, 2030, 2050.

Region / Country	Consumption				Production				Net Export			
	Observed	Difference from Ref			Observed	Difference from Ref			Observed	Difference from Ref		
	2020	2025	2030	2050	2020	2025	2030	2050	2020	2025	2030	2050
Africa	**7,821**	**−13**	**−15**	**10**	**3,260**	**32**	**55**	**121**	**−4,561**	**45**	**70**	**111**
Gabon	5	0	0	0	0	0	0	0	5	0	0	0
South Africa	2,009	1	3	2	1,801	22	38	119	209	23	41	122
N America	**82,076**	**−148**	**−130**	**122**	**83,070**	**585**	**324**	**180**	**995**	**733**	**454**	**58**
USA	65,165	111	102	99	67,291	42	255	53	2,127	153	153	152
Canada	5,190	18	11	3	9,108	544	577	264	3,918	562	588	261
S America	**16,008**	**−27**	**−22**	**22**	**15,631**	**−52**	**14**	**−3**	**−377**	**−25**	**36**	**−25**
Argentina	2,114	3	3	1	1,681	1	5	1	433	2	8	0
Brazil	9,034	15	13	17	10,463	54	0	12	1,429	39	13	30
Chile	1,075	3	2	1	966	1	3	13	109	4	5	13
Colombia	1,598	3	3	2	1,223	0	1	12	375	3	3	14
Asia	**211,131**	**−333**	**−255**	**0**	**202,164**	**392**	**380**	**493**	**−8,967**	**725**	**635**	**493**
China	123,315	201	129	71	118,000	445	471	1,004	5,315	647	600	1,075
India	17,492	11	15	12	17,284	11	14	11	208	0	0	0
Indonesia	7,323	13	13	17	11,954	62	136	561	4,631	49	122	578
Japan	23,269	39	34	37	23,942	21	21	11	672	18	13	48
Malaysia	2,809	4	4	5	1,750	14	25	7	1,059	18	29	3
Oceania	**3,795**	**−9**	**−6**	**2**	**3,761**	**16**	**24**	**198**	**−34**	**25**	**30**	**196**
Australia	3,037	7	4	3	3,076	4	18	177	39	3	14	174
New Zealand	690	1	2	2	683	21	42	20	7	22	44	22
Europe	**89,654**	**−1,017**	**−1,090**	**−1,512**	**103,008**	**−2,520**	**−2,313**	**−2,346**	**13,354**	**−1,504**	**−1,223**	**−834**
E. Union	**70,933**	**−105**	**−100**	**91**	**86,661**	**−453**	**−532**	**−469**	**15,729**	**−348**	**−432**	**−560**
Austria	2,175	3	3	3	4,924	38	18	22	2,749	41	21	25
Czech Rep.	1,454	1	2	3	847	1	2	1	607	1	4	4
Finland	947	1	1	1	9,122	262	406	511	8,175	261	405	512
Germany	18,545	27	26	28	22,184	30	42	359	3,640	3	16	331
Italy	10,734	17	12	13	9,103	3	15	159	1,631	15	27	172
Poland	7,349	15	15	14	5,127	20	38	5	2,222	34	52	19
Spain	6,676	2	6	2	6,453	2	16	7	224	0	22	5
Sweden	987	1	2	0	9,272	194	168	38	8,285	193	166	37
UK	7,657	11	10	11	3,672	78	97	101	3,985	89	106	90
Russia	7,148	269	207	8	9,402	1,268	1,078	918	2,254	1,536	1,284	926
Ukraine	1,406	1,166	1,184	1,625	1,018	943	860	1,103	388	223	324	522
World	**410,485**	**−1,546**	**−1,518**	**−1,356**	**410,896**	**−1,546**	**−1,517**	**−1,358**	**411**	**0**	**0**	**0**

et al. (2023), and Devadoss and Ridley (2024) also found that the lingering invasion by Russia on Ukraine led to significant disruptions to global wheat markets manifested in terms of increased global prices, reduced consumption, and economic losses in grain commodities and wheat markets, respectively. While not directly comparable, similar market outcomes were reported by Buongiorno and Johnston (2018a), which evaluated the potential effects of wood products trade restrictions on U.S. wood products markets, which were assumed to be imposed by the rest of the world as a countervailing measure to the U.S. protectionism policy. They found that such trade restrictions would increase product prices by up to 3% and overall welfare decline in the global forest products sector as well as in most of the countries. Our results are also in line with Pan et al. (2021), who evaluated the effects of increased U.S. tariffs to Chinese products by 25% to 35%. They indicated that such trade restrictions would lead to declined trade flows between China and the U.S., a part of which would be offset by other countries but leading to an overall decline in welfare of the global wood products sector.

Our projections suggest potential drastic changes in the global wood products markets in the next few decades. Global prices of industrial roundwood, sawnwood and paper products are projected to be higher until 2040, compared to the BAU trade scenario. Similarly, our model scenario projects significant trade displacements in most of the wood product markets in order to fill the void created by restrictions in Russian wood products in the current markets. Our analysis indicates that global markets will likely offset the restricted trade quantities of all products from Russia and Ukraine by adjusting production, consumption and trade quantities of industrial roundwood and finished wood products in individual countries. In doing so, most of the lost finished wood products (e.g., sawnwood, wood-based panels, and paper and paperboard) supply from Russia would likely be recovered by expanded production and reduced consumption of these products in other countries. However, because industrial roundwood is an input of finished wood products, and because each country has varying input-output coefficients, the new adjusted market in the trade restricted scenario would likely lead to net declines in the global production and consumption of industrial roundwood, suggesting a likely deadweight loss in the global timber markets. For example, projected market adjustments in individual countries in the trade restricted scenario were shown to lead to declines in the global industrial roundwood production by 28, 29 and 18 million m^3 by 2025, 2030, and 2050, respectively, relative to the respective BAU projected levels. As noted above, these reductions in global industrial roundwood production did not translate into similar reductions in the production of finished goods at the global level due to a combination of factors including 1) altered prices (higher than BAU levels) of both industrial roundwood and finished wood products that changed production, consumption, and trade quantities of both roundwood and finished products in other countries, and 2) varying (lower) input/output coefficients (amount of roundwood input needed to manufacture finished wood products) in other countries relative to Russia and Ukraine.

These declines in global roundwood production occurred even though most of the countries ramped up their industrial roundwood production either to fulfill their domestic demand or to meet the void in world import demand due to restrictions on roundwood trade from Russia and Ukraine. Specifically, the USA, Canada, China, Brazil, and the European Union region are expected to notably increase their production of industrial roundwood in the short run (until 2030), but their production is projected to eventually go down by 2050 as Russia

Table 6
Base year values and projected changes in consumption, production and net export (thousand metric tons) of total wood pulp between the reference and the trade constrained scenarios by world regions and selected countries, 2025, 2030, 2050.

Region / Country	Consumption				Production				Net Export			
	Observed	Difference from Ref			Observed	Difference from Ref			Observed	Difference from Ref		
	2020	2025	2030	2050	2020	2025	2030	2050	2020	2025	2030	2050
Africa	**1,665**	**23**	**34**	**59**	**1,169**	**18**	**34**	**88**	**−496**	**−5**	**0**	**29**
Gabon	0	0	0	0	0	0	0	0	0	0	0	0
South Africa	1,057	12	19	54	1,045	12	28	74	12	0	8	20
N America	**55,966**	**248**	**66**	**58**	**64,616**	**532**	**498**	**365**	**8,650**	**285**	**432**	**307**
USA	48,205	21	175	34	49,679	506	452	115	1,475	485	627	149
Canada	6,673	228	240	101	14,796	33	52	250	8,123	195	188	149
S America	**7,925**	**−35**	**0**	**16**	**29,777**	**320**	**−222**	**−1,269**	**21,853**	**355**	**−223**	**−1,285**
Argentina	693	1	1	0	630	35	50	53	63	36	48	53
Brazil	5,702	35	5	8	21,049	180	275	1,225	15,347	215	270	1,233
Chile	843	1	3	11	5,138	98	2	92	4,295	97	5	103
Colombia	391	0	0	4	235	7	4	5	156	7	4	1
Asia	**63,979**	**71**	**36**	**−28**	**34,814**	**−161**	**101**	**−43**	**−29,165**	**−232**	**65**	**−15**
China	37,782	127	119	158	13,049	221	406	129	24,733	93	287	30
India	4,171	3	3	1	3,107	30	39	9	1,064	33	42	10
Indonesia	4,661	24	55	133	8,610	411	362	255	3,949	387	307	121
Japan	8,909	10	9	11	7,691	69	55	145	1,218	59	45	156
Malaysia	314	3	4	3	131	3	7	0	183	6	11	3
Oceania	**2,042**	**4**	**8**	**82**	**2,808**	**−13**	**−8**	**46**	**766**	**−16**	**−16**	**−36**
Australia	1,710	5	10	75	1,397	19	27	29	313	14	17	46
New Zealand	331	9	17	7	7	19	17		1,080	3	2	11
Europe	**47,307**	**−983**	**−844**	**−814**	**46,987**	**−1,370**	**−1,104**	**185**	**−320**	**−387**	**−260**	**999**
E. Union	**38,972**	**−403**	**−469**	**−591**	**37,315**	**−204**	**−430**	**−496**	**−1,657**	**199**	**39**	**96**
Austria	1,858	20	12	3	1,610	20	12	3	248	0	0	1
Czech Rep.	181	0	1	0	0	0	0	0	181	0	1	0
Finland	7,047	219	328	408	11,037	219	328	165	3,990	0	0	243
Germany	5,157	25	19	20	2,302	50	135	0	2,855	25	116	20
Italy	3,540	1	4	34	266	3	6	22	3,274	4	2	12
Poland	2,601	5	13	7	1,636	64	26	31	964	59	13	39
Spain	1,755	1	5	3	1,660	1	5	53	95	0	0	50
Sweden	8,166	165	138	36	11,463	166	138	222	3,298	0	0	186
UK	1,095	24	28	23	400	14	7	15	695	10	22	8
Russia	6,438	562	360	224	8,586	1,205	696	650	2,148	643	336	874
Ukraine	72	65	61	32	0	0	0	0	72	65	61	32
World	**178,884**	**−672**	**−701**	**−627**	**180,171**	**−673**	**−701**	**−628**	**1,287**	**0**	**0**	**0**

recovers the majority of its lost industrial roundwood and sawnwood market by 2050 (Tables 2 and 3), which could be the result of Russia likely capitalizing its competitive advantage in both roundwood and sawnwood production and trade as global markets adjusted to BAU levels. Impacts observed in the European Union's markets merit further discussion. Although the European Union responded to higher production and consumption of industrial roundwood in 2025 in response to restricted trade in Russia and Ukraine, it was shown to contract its consumption notably in the later years of projection (by 27 million m^3 in 2050) through reduced production (by 5 million m^3), and higher net exports (by 22 million m^3) (Table 2). Such a change in the EU roundwood market was due to a reduced need to expand its production and export of finished products, which uses industrial roundwood as a feedstock, as Russia and Ukraine expanded its production and exports of industrial roundwood and sawnwood after their market recovered post 2045 (Table 3). In contrast, the European Union region expanded its wood-based panels production and export throughout the projection period, replacing import demand for these products from Russia.

In contrast to the projected outcomes for industrial roundwood markets in individual countries, the trade restrictions scenario showed somewhat declined consumption of finished wood products in almost all countries, at least until 2030, and declined production in several countries suggesting a potential economic loss to consumers of finished wood products in all countries and to producers of those products in most of the countries. However, some countries expanded their finished wood products similar to industrial roundwood, either to fulfill their domestic demand or to supply to the world to meet the import demand. Specifically, countries such as China, USA, and the European Union countries such as Germany and Austria, were shown to notably increase their sawnwood production and net export in the restricted trade scenarios throughout the projection period (Table 3).

The projected altered production and trade of timber and finished wood products in individual countries due to the Russian invasion of Ukraine has both economic and environmental implications for the national, regional, and the global forest products sector. While trade displacement could boost the economic potential of timber production and wood-based industries in other countries, they are also likely to lead to loosening environmental restrictions, more timber logging, and deforestation (Speed, 2022). It has been estimated that approximately 26% of deforestation can be attributed to international demands, with the majority of the deforestation being exported to countries with decreasing deforestation rates or increases in forest cover (Pendrill et al., 2019). Hence, countries that are already suffering from rampant illegal logging and deforestation will likely bear the additional harvest pressure from altered global demand and supply conditions, which could lead to deforestation and degradation specifically in developing countries where poor governance and political instability usually fuel illegal felling (Robalino and Herrera, n.d.).

While our results provide new insights into the near- and the long-term impacts on the global wood products market of ongoing Russian invasion of Ukraine, they should be interpreted with caution as they can be sensitive to our assumption of when the invasion ends, and how bilateral trade relationships of Russian partner countries change over time. We expect a longer market recovery period if invasion continues longer than assumed in our study. Moreover, we expect different projected market outcomes if additional countries sanction Russian trade or lift the trade ban sooner or later than assumed in this study. We note that even if the invasion ends and sanctions are lifted immediately after

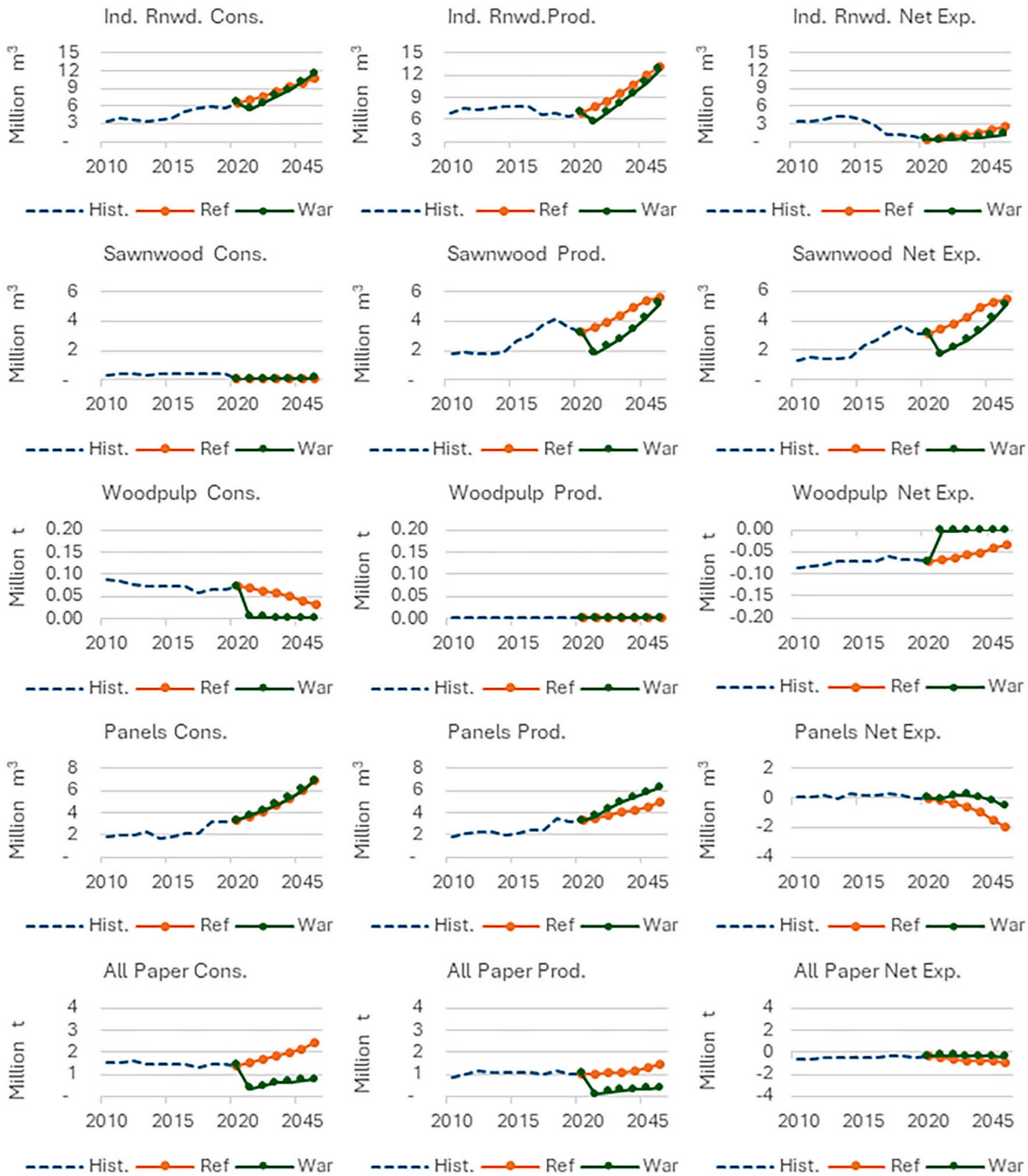

Fig. 3. Projected consumption, production, and export, and net trade of wood products for Ukraine in the business-as-usual reference and the trade constrained scenarios, 2020–2050.

2025, as assumed in this study, it may take a while for the war-torn countries to build up their damaged infrastructure and lost capital, labor resources, and industry capacities, hinting that the market recovery period for Russia and Ukraine could be longer than that projected in our scenarios. Another caveat of our study is that it assumes same GDP growth between the BAU and invasion scenario. However, it is possible that GDP growth in Russia and Ukraine and possibly in Europe and elsewhere are affected (likely lower GDP growth) due to Russian invasion of Ukraine, which could render different forest products market outcomes than projected in this study.

Like in the case of all forest sector models, another caveat of our study is that GFPM also assumes same market conditions in the future as represented by the historical relationship between a market driver and a forest product variable. These relationships are represented in the model by various parameters of demand, supply, forest area, forest stock, manufacturing activities, and transport. Our results are uncertain to the extent that the future markets conditions and the associated parameters differ from historical market conditions. In addition, inherent to all model projections, projected results in this study can be sensitive to the specified model parameters and data uncertainty in GFPM. For example, Buongiorno and Johnston (2018b), evaluated the sensitivity of parameters and data uncertainty to the long run projections in GFPM and found that parameter uncertainty led to steadily increasing variability of projections with time, and that demand and supply elasticities tended to dominate the effect of uncertainties in parameters on projected outcomes.

However, despite these uncertainties, we believe that the general direction and the degrees of the magnitudes of the projected effects of Russian invasion of Ukraine on the global forest products markets would remain valid and therefore are useful to the global, regional, and

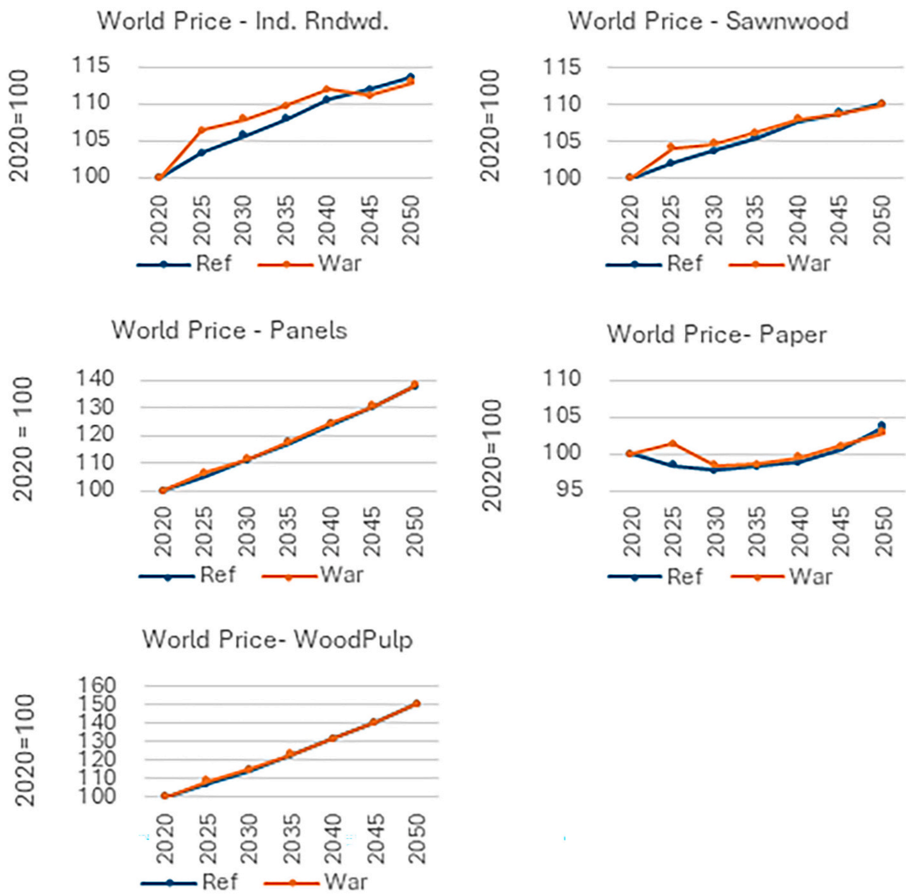

Fig. 4. Projected world price of industrial roundwood, sawnwood, wood-based panels, paper and paperboard, and wood pulp in the business-as-usual reference and the trade constrained scenarios, 2020–2050.

national wood products sector stakeholders. Future research can be aimed to quantify the overall welfare impacts as well as economy-wide impacts of the invasion on the global forest products sector based on partial or general equilibrium frameworks.

CRediT authorship contribution statement

Prakash Nepal: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Austin Lamica:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Rajan Parajuli:** Writing – review & editing, Writing – original draft, Resources, Methodology, Investigation, Formal analysis, Conceptualization.

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. Key equations, parameters and variables used in GFPM base model

The global market modeling in GFPM occurs at two phases: static and dynamic.

A.1. Static phase

Following Samuelson (1952), the static phase spatial global market equilibrium of the wood products sector in a given year is obtained by maximizing the sum of the consumers' and producers' surplus for all products and countries as follows:

$$maxZ \;=\; \sum_i\sum_k\int_0^{D_{ik}} P_{ik}(D_{ik})dD_{ik} \qquad \sum_i\sum_k\int_0^{S_{ik}} P_{ik}(S_{ik})dS_{ik} \qquad \sum_i\sum_k\int_0^{Y_{ik}} m_{ik}(Y_{ik})dY_{ik} \qquad \sum_i\sum_j\sum_k c_{ijk}T_{ijk} \tag{1}$$

where: i and j refer to countries and k refers to a product. P is price in U.S. dollars of constant value, D is final product demand, S is raw material supply, Y is quantity manufactured, m is cost of manufacture (labor, capital, and materials excluding wood and fiber), T is quantity transported, and c is freight cost (cost of transport plus tariff).The above objective function is maximized subject to series of specified constraints related to end product demand (eq. [2]), raw material supply (eq. [3]), wood drain (eq. [4]), material balance (eq. [5]), trade inertia (eq. [6]), manufacturing costs (eq. [7]), and transport cost (eq. [8] and [9]).

$$D_{ik} = D^*_{ik}\left(\frac{P_{ik}}{P_{ik,\ 1}}\right)^{\delta_{ik}} \tag{2}$$

where D^* = current consumption at last period's price, $P\text{-}1$ = last period's price, and δ = price elasticity of demand. As shown in the section on the dynamic phase below, D* depends on last period's demand, the growth of GDP in the country, and other exogenous or endogenous demand shifters.

$$S_{ik} = S^*_{ik}\left(\frac{P_{ik}}{P_{ik,\ 1}}\right)^{\lambda_{ik}} \tag{3}$$

where: S^* = current supply at last period's price, and λ = price elasticity of supply. As shown in the dynamic phase below, S* depend on last period's supply, and on exogenous or endogenous supply shifters, especially the forest stock.

$$S_i = \;\; S_{ir} + S_{in} + \theta_i S_{if}\big)\mu_I \tag{4}$$

where r = industrial roundwood, n = other industrial roundwood, f = fuelwood, $0 \leq \theta_i \leq 1$ = fraction of fuelwood that comes from the forest, $\mu \geq 1$ = ratio of drain from forest stock to harvest.

$$\sum_j T_{jik} + S_{ik} + Y_{ik} \quad D_{ik} \quad \sum_n a_{ikn}Y_{in} \quad \sum_j T_{ijk} = 0 \;\; \forall_{i,k} \tag{5}$$

where: a_{ikn}= input of product k per unit of product n. According to eq. [5], in each country and for each product, the quantity imported, domestic supply, and the manufactured quantity must equal the domestic demand plus the quantity used in manufacturing other products, plus exports.

$$T^L_{ijk} \leq T_{ijk} \leq T^U_{ijk} \tag{6}$$

Eq. [6] defines the trade inertia constraints, which keep the current trade quantity within a lower bound (L) and an upper bound (U), relative to the previous period.

$$m = m^*_{ik}\left(\frac{Y_{ik}}{Y_{ik,\ 1}}\right)^{s_{ik}} \tag{7}$$

where: m^* = current manufacturing cost at last period's output and s = elasticity of manufacturing cost with respect to output. As shown in the dynamic phase section below, m^* depend on last period's manufacturing cost and on the exogenous rate of change of manufacturing cost.

$$c_{ijk} = c^*_{ijk}\left(\frac{T_{ijk}}{T_{ijk,\ 1}}\right)^{\tau_{ijk}} \tag{8}$$

where: c^* = current transport cost at last period's trade, and τ = elasticity of transport cost with respect to trade quantity. As shown in the next section, c^* depends on last period's transport cost and on the exogenous changes of freight rates and taxes. In the base year, c^* is computed as:

$$c_{ijk} = f_{ijk} + t^X_{jk}\;\; P_{ik,\ 1}\big) + t^I_{jk}\left(f_{ijk} + P_{ik,\ 1}\right) \tag{9}$$

where: c = transport cost, per unit of volume, f = freight cost, per unit of volume, t^X = export tax, t^I= import ad-valorem tariff, and $P_{\ 1}$ is equal to the observed base-year world export price.

A.2. Dynamic phase

In the dynamic phase, projections from the base year to future years are provided at 5 years interval through calculation of the changes in the condition of the global equilibrium from one period to the next, as summarized in equations representing demand shift [10], supply shift [11], forest area change [12], forest stocks change [13], changes in input-output coefficients [14], changes in manufacturing cost [15], changes in transportation costs [16], and changes in trade inertia bounds [17].

$$D^* = D_{\ 1}\left(1 + \alpha_y g_y + \alpha_0\right) \tag{10}$$

where: g_y = GDP periodic growth rate, α_y = elasticity with respect to GDP, and α_0= periodic trend.

$$S^* = S_{\ 1}\,(1 + \beta_I g_I + \beta_a g_a) \tag{11}$$

where, g_I = the endogenous periodic rate of change of forest stock; g_a = the endogenous periodic rate of change of forest area, and β_I and β_a are respective elasticities.

$$A = (1 + g_a)A_{\ 1} \tag{12}$$

where: A = forest area, and g_a = periodic rate of forest area change

$$I = (I_{\ 1} + \mathrm{G}_{\ 1} \quad pS_{\ 1}) \tag{13}$$

where: I is the forest stock at the beginning of the current period and $G_{\ 1}$ is the change of forest stock without harvest during the previous period.

$$a = a_{\ 1} + \Delta a \tag{14}$$

where: Δa = periodic change in input-output coefficient.

$$m^* = m_{\ 1}(1 + g_m) \tag{15}$$

where: g_m= exogenous rate of a periodic change in manufacturing costs

$$c^* = c_{\ 1} + \Delta f + t^x p_{\ 1} \quad t^x p_{\ 2} + t^I(f + p_{\ 1}) \quad t^I_{\ 1}(f_{\ 1} + p_{\ 2}) \tag{16}$$

where: $f = f_{\ 1} + \Delta f$ and $t = t_{\ 1} + \Delta$t, and $\Delta f and\ \Delta t$ are periodic changes in freight cost and taxes, respectively.

$$T^L = \mathrm{T}_{\ 1}(1 \quad \varepsilon)^p T^U = \mathrm{T}_{\ 1}(1 + \varepsilon)^p \tag{17}$$

where: ε = exogenously specified absolute value of the maximum annual rate of change in trade flow.

Table A1. Manufacturing parameters and variables specified in the 2023 version of GFPM with base year 2020 and used in this study.[a]

Commodity	Elasticity of demand w.r.t.:		Elasticity of supply w.r.t.:		Growth rate of shifter	
	Price[b]	GDP[b]	Price[b]	Growing stock[b]	Demand shifter (GDP)[c]	Supply shifter (grow. stock)[d]
Ind. roundwood	*	*	1.31	1.1	*	Varies by country
Sawnwood	0.17	0.24	**	**	Varies by country	**
Wood-based panels						
Plywood/veneer	0.33	0.72	**	**	Varies by country	**
Particleboard	0.51	0.59	**	**	Varies by country	**
Fiberboard	0.54	0.92	**	**	Varies by country	**
Woodpulp						
Mechanical pulp	***	***	***	***	Varies by country	***
Chemical pulp	***	***	***	***	Varies by country	***
Paper & paper board						
Newsprint	0.25	0.42	**	**	Varies by country	**
Print. & wrt. Paper	0.53	0.59	**	**	Varies by country	**
Other paper & papbd.	0.45	0.40	**	**	Varies by country	**

[a] GFPM also models fuelwood, other industrial roundwood, other fiber pulp, and waste paper, but are not shown in this table.
[b] Estimated and reported in various publications and adjusted by the GFPM developer for calibration.
[c] Exogenous. Projected in B2 scenario of Intergovernmental Panel on Climate Change (IPCC).
[d] Endogenous. Calculated by the model as last year's growing stock plus growth minus harvest.
[*] Derived demand; demand curve not specified.
[**] Derived supply; supply curve not specified.
[***] Intermediate products, quantity manufactured derived from demand for finished products, demand and supply curve not specified.

Table A2. Manufacturing parameters and variables specified in the 2023 version of GFPM with base year 2020 and used in this study.[a]

Commodity	Manufacturing Activity			Rate of change in	
	Manuf. cost	Elasticity of output w.r.t. manu. Cost	Input/output coefficient	Manuf. cost[b]	Input/output coefficient[c]
Ind. roundwood	N/A (Raw material)	0.1	N/A (Raw material)	N/A (Raw material)	N/A (Raw material)
Sawnwood	Varies by country	0.1	Varies by country	Varies by country	Varies by country
Wood-based panels					
Plywood/veneer	Varies by country	0.1	Varies by country	Varies by country	Varies by country
Particleboard	Varies by country	0.1	Varies by country	Varies by country	Varies by country
Fiberboard	Varies by country	0.1	Varies by country	Varies by country	Varies by country

(continued on next page)

(*continued*)

Commodity	Manufacturing Activity			Rate of change in	
	Manuf. cost	Elasticity of output w.r.t. manu. Cost	Input/output coefficient	Manuf. cost[b]	Input/output coefficient[c]
Woodpulp					
Mechanical pulp	Varies by country	0.1	Varies by country	Varies by country	Varies by country
Chemical pulp	Varies by country	0.1	Varies by country	Varies by country	Varies by country
Paper & paper board					
Newsprint	Varies by country	0.1	Varies by country	Varies by country	Varies by country
Print. & wrt. Paper	Varies by country	0.1	Varies by country	Varies by country	Varies by country
Other paper & papbd.	Varies by country	0.1	Varies by country	Varies by country	Varies by country

N/A = Not applicable.
[a] GFPM also models fuelwood, other industrial roundwood, other fiber pulp, and waste paper, but are not shown in this table.
[b] Exogenous. Estimated by the GFPM developer using historical data.
[c] Exogenous. Represents changes in technology. Estimated by the authors of GFPM using historical data.

Table A3. Transport parameters and variables specified in the 2023 version of GFPM with base year 2020 and used in this study.[a]

Commodity	Freight cost of shipping one unit of commodity from origin to destination	Import ad-valorem tax rate[b]	Trade inertia constraint[b]
Ind. roundwood	$16.74/m^3	Varies by country from 0 to 0.30	Varies by countries from 0 to 0.06
Sawnwood	$29.81/m^3	Varies by country from 0 to 0.40	Varies by countries from 0 to 0.04
Wood-based panels			
Plywood/veneer	$22.48/m^3	Varies by country from 0 to 0.30	Varies by countries from 0 to 0.04
Particleboard	$11.32/m^3	Varies by country from 0 to 0.30	Varies by countries from 0 to 0.07
Fiberboard	$14.64/m^3	Varies by country from 0 to 0.30	Varies by countries from 0 to 0.08
Woodpulp			
Mechanical pulp	$37.04/ton	Varies by country from 0 to 0.26	Varies by countries from 0 to 0.01
Chemical pulp	$43.76/ton	Varies by country from 0 to 0.26	Varies by countries from 0 to 0.05
Paper & paper board			
Newsprint	$21.28/ton	Varies by country from 0 to 0.26	Varies by countries from 0 to 0.30
Print. & wrt. Paper	$52.14/ton	Varies by country from 0 to 0.26	Varies by countries from 0 to 0.06
Other paper & papbd.	$52.62/ton	Varies by country from 0 to 0.30	Varies by countries from 0 to 0.07

[a] GFPM also models fuelwood, other industrial roundwood, other fiber pulp, and waste paper, but are not shown in this table.
[b] Estimated by the GFPM developer using historical data.

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