



Article GFPMX: A Cobweb Model of the Global Forest Sector, with an Application to the Impact of the COVID-19 Pandemic

Joseph Buongiorno

Department of Forest and Wildlife Ecology, University of Wisconsin, Madison, WI 53705, USA; jbuongio@wisc.edu

Abstract: The GFPMX projects forest area and stock, consumption, production, imports, exports, and prices of industrial roundwood, fuelwood, sawnwood, wood-based panels, wood pulp, and paper and paperboard in 180 countries, and currently from 2018 to 2070. The core principle of the model is the cobweb theorem, according to which markets are not necessarily in equilibrium, but take some time to adjust to shocks—such as demand shifts—leading to oscillatory dynamics of prices and quantities. This paper presents the model's structure and the estimation of its parameters from international statistics on production, trade, forest area, and forest stock. This is followed by an application of the GFPMX to the impact on the global forest sector of the economic recession caused by the COVID-19 pandemic.

Keywords: forestry; forest industries; forest products trade; modeling; cobweb; COVID-19



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1. Introduction

This paper presents a model of the global forest sector, GFPMX, designed to project the forest area and stock for multiple countries and years, along with the annual consumption, production, import, export, and price of major wood products.

Unlike other forest sector models [1–4] that use partial equilibrium theory [5,6], the GFPMX relies on the cobweb theorem [7–9]. In this view, instead of following a succession of perfect equilibria, a dynamic economy tends to only converge gradually towards an equilibrium, typically in oscillating patterns, without necessarily reaching it.

The proposed model also assumes that demand creates its own supply [10], in contrast with Say's law [11]. Thus, in the GFPMX, domestic and import demand are the driving forces in the evolution of the global forest sector. Export supply is pulled by the global demand for imports, and domestic production meets net demand (consumption minus imports plus exports). The world price then depends on production, the price of inputs, and forest stock, while the local price is a function of the world price. Forest area changes along an environmental Kuznets curve [12], while forest stock varies according to a growth–drain equation [13].

The first part of this paper presents the mathematical formulation of the GFPMX. This is followed by a description of the methods used to estimate the model parameters, and of the Excel[©] software employed to implement the model. As an example of potential applications, the GFPMX was used to project the effects on the global forest sector of the economic recession induced by the COVID-19 pandemic—a catastrophe "unprecedented in its global reach and impact, posing formidable challenges to policymakers and to the empirical analysis of its direct and indirect effects within the interconnected global economy" [14]. The GFPMX was applied to simulate two scenarios, with and without the COVID-19 pandemic, based on the economic growth projections of the International Monetary Fund. Due to the pandemic, the global production of forest industries was nearly 35 billion less (-2.7%) in 2020 and still 32 billion less in 2030, while global trade was 11 billion less (-4.5%) in 2020 and nearly 10 billion less in 2030.

2. Model Formulation

The GFPMX model was designed to predict for each county (i) and year (t) the consumption, production, import, export, and price of fuelwood (f), industrial roundwood (r), sawnwood (s), wood-based panels (l), wood pulp (u), and paper and paperboard (a). The model also projects for each year and country the forest area and the volume of growing stock.

2.1. Domestic Demand of End Products

The consumption of each of these end products is a function of the local price lagged one period (in accordance with the cobweb theorem), and of the current gross domestic product, with country- and product-specific parameters:

$$C_{ikt} = \alpha_{ik} P_{ik,t-1}^{\beta_{ik}} Y_{it}^{\gamma_{ik}} \quad \forall k = f, s, l, a$$
(1)

 C_{ikt} = consumption of product *k* in country *i* and year *t*;

 $P_{ik,t-1}$ = lagged price of product *k* in country *i*;

 Y_{it} = gross domestic product in country *i* and year *t*;

 $\alpha_{ik}, \beta_{ik}, \gamma_{ik}$ = country- and product-specific parameters;

f = fuelwood; s = sawnwood; l = wood-based panels; a = paper and paperboard

2.2. Domestic Demand for Wood Pulp

Wood pulp is used to make paper and paperboard. Depending on its price, wood pulp can be substituted by other fibers. Thus, domestic consumption is a function of the local price of wood pulp lagged one period, and of the production of paper and paperboard, with country-specific parameters:

$$C_{iut} = \alpha_{iu} P^{\beta_{iu}}_{iu,t-1} Q^{\gamma_{iu}}_{iat} \tag{2}$$

 C_{iut} = consumption of wood pulp in country *i* and year *t*;

 $P_{iu,t-1}$ = lagged price of wood pulp in country *i*;

 Q_{iat} = production of paper and paperboard in country *i* and year *t*;

 $\alpha_{iu}, \beta_{iu}, \gamma_{iu}$ = country-specific parameters.

2.3. Domestic Demand for Industrial Roundwood

The domestic consumption of industrial roundwood is a function of its price lagged one period, and of the production of products made with industrial roundwood, with country-specific parameters:

$$C_{irt} = \alpha_{ir} P_{ir,t-1}^{\beta_{ir}} (Q_{ist} + Q_{ilt} + Q_{iut})^{\gamma_{ir}}$$
(3)

C_{irt} = consumption of industrial roundwood in country *i* and year *t*;

 $P_{ir,t-1}$ = lagged price of industrial roundwood in country *i*;

 Q_{ist} , Q_{ilt} , Q_{iut} = production of sawnwood, wood-based panels, and wood pulp, respectively; α_{ir} , β_{ir} , γ_{ir} = country-specific parameters.

The import demand equations have the same form as the domestic demand Equations (1)–(3), but with different product- and country-specific parameters. Furthermore, the price is augmented by potential import tariffs.

2.4. Import Demand for Fuelwood, Sawnwood, Panels, Paper and Paperboard

$$I_{ikt} = \alpha_{ik} [(1 + \tau_{ik,t-1}) P_{ik,t-1}]^{\beta_{ik}} Y_{it}^{\gamma_{ik}} \forall k = f, s, l, a$$
(4)

 I_{ikt} = import of product *k* in country *i* and year *t*;

 $P_{ik,t-1}$ = lagged price of product *k* in country *i*;

 Y_{it} = gross domestic product in country *i* and year *t*;

 $\tau_{ik,t-1}$ = ad valorem tariff on imports of product *k* in country *i*, at *t* - 1; α_{ik} , β_{ik} , γ_{ik} = country- and product-specific parameters.

2.5. Import Demand for Wood Pulp

$$I_{iut} = \alpha_{iu} [(1 + \tau_{iu,t-1}) P_{iu,t-1}]^{\beta_{iu}} Q_{iat}^{\gamma_{iu}}$$
(5)

 I_{iut} = import of wood pulp in country *i* and year *t*; $P_{iu,t-1}$ = lagged price of wood pulp in country *i*; Q_{iat} = production of paper and paperboard in country *i* and year *t*; $\tau_{iu,t-1}$ = ad-valorem tariff on imports of wood pulp in country *i*, at t - 1; $\alpha_{iu}, \beta_{iu}, \gamma_{iu}$ = country-specific parameters.

2.6. Import Demand for Industrial Roundwood

$$V_{irt} = \alpha_{ir} [(1 + \tau_{ir,t-1}) P_{ir,t-1}]^{\beta_{ir}} (Q_{ist} + Q_{ilt} + Q_{iut})^{\gamma_{ir}}$$
(6)

 I_{irt} = import of industrial roundwood in country *i* and year *t*;

 $P_{ir,t-1}$ = lagged price of industrial roundwood in country *i*;

 Q_{ist} , Q_{ilt} , Q_{iut} = production of sawnwood, wood-based panels, and wood pulp, respectively; $\tau_{ir,t-1}$ = ad valorem tariff on imports of industrial roundwood in country *i*, at t - 1; α_{ir} , β_{ir} , γ_{ir} = country-specific parameters.

2.7. Export Supply

Exports of a product from a country depend on the volume of global imports according to a "marginal propensity to export" equation, analogous to the "marginal propensity to consume" of macroeconomics—a linear function of world imports. This functional form and the country-specific parameters estimated by ordinary least squares ensure that the sum of all countries' predicted exports equals total world imports (a difference may remain insofar as the data on world imports differ from world exports):

$$X_{ikt} = \delta_{ik} + \theta_{ik} I_{wkt} \quad \forall k = f, s, l, a, u, r$$
(7)

 X_{ikt} = export of product k from country i in year t; $I_{wkt} = \sum_{i=1}^{n} I_{ikt}$ = world imports of product k in year t, n = number of countries; δ_{ik}, θ_{ik} = country- and product-specific parameters; θ_{ik} = marginal propensity to export product k from country i.

2.8. Domestic Production

For each product and country, the domestic production is assumed to meet net demand, determined by domestic consumption (Equations (1)–(3)), imports (Equations (4)–(6)), and exports (Equation (7)), according to:

$$Q_{ikt} = C_{ikt} + X_{ikt} - I_{ikt} \quad \forall k = f, s, l, a, u, r$$
(8)

 Q_{ikt} = production of product *k* in country *i* and year *t*.

2.9. World Price of Industrial Roundwood

The world price of industrial roundwood is a function of the quantity produced (as in an inverse supply function), of the level of growing stock, and of a time trend:

$$P_{wrt} = \vartheta_r Q_{wrt}^{\mu_r} S_{wt}^{\pi_r} e^{\rho_r t}$$
⁽⁹⁾

 P_{wrt} = world price of industrial roundwood in year *t*;

 $Q_{wrt} = \sum_{i=1}^{n} Q_{irt}$ = world production of industrial roundwood in year *t*, in *n* countries; $S_{wkt} = \sum_{i=1}^{n} S_{ikt}$ = world forest growing stock in year *t*, in *n* countries; ϑ_r , μ_r , π_r , ρ_r = parameters.

2.10. World Price of Fuelwood, Sawnwood, Wood Pulp, and Wood-Based Panels

For these products the world price is a function of the world price of industrial roundwood, the main input for sawnwood, wood pulp, and wood-based panels, and the main competitor for fuelwood:

$$P_{wkt} = \vartheta_k P_{wr,t}^{\pi_k} \quad \forall k = f, s, u, l \tag{10}$$

 P_{wkt} = world price of product *k* in year *t*; P_{wrt} = world price of industrial roundwood in year *t*; ϑ_k , π_k = parameters.

2.11. World Price of Paper and Paperboard

The world price of paper and paperboard depends on the world price of wood pulp (the main input in making paper and paperboard):

$$P_{wat} = \vartheta_a P_{wut}^{\pi_a} \tag{11}$$

 P_{wat} = world price of paper and paperboard in year *t*; P_{wut} = world price of wood pulp in year *t*; ϑ_a , π_a = parameters.

2.12. Local Price

The local price, one of the determinants of domestic and import demand, depends on the world price:

$$P_{ik,t} = \sigma_{ik} P_{wk,t}^{\iota_{ik}} \quad \forall i,k,t \tag{12}$$

 $P_{ik,t}$ = price of product *k* in country *i* and year *t*;

 $P_{wk,t}$ = world price of product *k* in country *i* and year *t*; σ_{ik} , τ_{ik} = parameters.

2.13. Forest Area

Forest area changes at an annual rate that depends on economic development:

$$A_{it} = A_{i,t-1}(1+g_{i,t}) \tag{13}$$

 A_{it} = forest area in country *i* and year *t*;

 g_{it} = annual growth rate of forest area, in country *i* and year *t*. This growth rate changes over time according to an "environmental Kuznets curve" equation linking the rate of growth to the level of GDP per capita:

$$g_{it} = (\varphi_i + \omega y_{it})e^{\vartheta y_{it}} \tag{14}$$

 y_{it} = GDP per capita in country *i* and year *t*;

 φ_i = country-specific constant;

 ω , ϑ = parameters. With $\omega > 0$ and $\vartheta < 0$, the growth rate of forest area is negative at low levels of GDP per capita—implying deforestation—becomes positive at higher levels—implying afforestation—and converges to zero with positive values at very high levels of GDP per capita, implying a stabilization of forest area.

2.14. Forest Stock

The forest stock in each country changes over time according to the following growthdrain equation:

$$S_{it} = S_{i,t-1}(1+\sigma_i) - \alpha_i(Q_{if,t-1}+Q_{ir,t-1})$$
(15)

 S_{it} = forest stock in country *i* and year *t*;

 $Q_{if,t-1}$ = lagged fuelwood production in country *i*; $Q_{ir,t-1}$ = lagged industrial roundwood production in country *i*; σ_i = growth rate of forest stock, without harvest, in country *i*; $\alpha_i > 0$ = influence of harvest on forest stock in country *i*.

3. Data and Parameters Estimation

3.1. Data

The data used to estimate the parameters of the GFPMX equations were annual statistics from 180 countries, from 1992 to 2018. The data on production, imports, and exports in quantity and value came from FAOSTAT [15]. The data on population and real GDP in constant United States dollars (USD), and the data on the United States GDP deflator, came from the World Bank Development Indicators database [16]. The world price for each commodity group was the unit value of world exports, and the local price was the unit value of imports for net exporting countries, or the unit value of exports for net exporting countries. For countries with no import or export the local price was the world price. All prices were expressed in constant United States dollars of 2017. The data on forest area and forest stock came from the Forest Resources Assessment of the Food and Agriculture Organization of the United Nations [17].

3.2. Domestic Demand and Import Demand Parameters

The country-specific parameters of Equations (1)–(6) were obtained by minimizing the sum of the squares of the differences between the observed and predicted logarithm of consumption, or imports, given the local price and demand shifters, for all products and countries, conditional on a priori upper and lower bounds on the elasticities. For example, the country- and product-specific parameters of the domestic demand Equation (1) were obtained by solving the following quadratic program [18]:

Find the parameters $\beta_{ik}^+, \beta_{ik}^-, \gamma_{ik}^+, \gamma_{ik}^-, \alpha_{ik}^+, \alpha_{ik}^- \ge 0 \ \forall i, k;$

such that:

$$\min SSQR = \sum_{ikt} \left(lnC_{ikt} - ln\hat{C}_{ikt} \right)^2$$
(16)

subject to:

$$ln\hat{C}_{ikt} = \beta_{ik}lnP_{ik,t-1} + \gamma_{ik}lnY_{ikt} + \alpha_{ik} \ \forall i,k$$
(17)

$$\beta_{ik}^{L} \le \beta_{ik} = \beta_{ik}^{+} - \beta_{ik}^{-} \le \beta_{ik}^{U} \,\forall i,k \tag{18}$$

$$\gamma_{ik}^{L} \le \gamma_{ik} = \gamma_{ik}^{+} - \gamma_{ik}^{-} \le \gamma_{ik}^{U} \,\forall i,k \tag{19}$$

$$\alpha_{ik} = \alpha_{ik}^+ - \alpha_{ik}^- \,\forall i,k \tag{20}$$

where the superscripts L and U in Equations (18) and (19) refer to a priori lower and upper bounds on the parameters.

The results summary for domestic demand (Table 1) shows that the mean price elasticity of demand, over all countries, varied from -0.38 for paper and paperboard to -0.16 for industrial roundwood. The mean GDP elasticity varied from 0.17 for fuelwood to 0.67 for wood-based panels. The mean elasticity of wood pulp demand with respect to paper and paperboard production was 0.75, while the mean elasticity of industrial roundwood demand with respect to the sum of sawnwood, wood-based panels, and pulp production was 0.56. All mean values of the elasticities were statistically significant at least at the 0.01 level.

For import demand (Table 2), the mean price elasticity over all countries varied from -0.47 for paper and paperboard to -0.12 for fuelwood. The mean GDP elasticity varied from 0.15 for fuelwood to 0.75 for wood-based panels. The mean elasticity of wood pulp import demand with respect to paper and paperboard production was 0.62, and the mean elasticity of industrial roundwood import demand with respect to the sum of sawnwood, wood-based panels, and pulp production was 0.28. All mean values of the elasticities were statistically significant at least at the 0.01 level.

D 1 <i>i</i>	Elasticity			D 1 (Elasticity	
Product –		Price	Shifter	- Product -		Price	Shifter
Sawnwood ¹	max	-0.05	1.00	Wood pulp ²	max	-0.05	1.00
	min	-1.00	0.00		min	-1.00	0.00
	mean	-0.31	0.45		mean	-0.28	0.75
	SE	0.02	0.03		SE	0.03	0.03
Wood-based panels ¹	max	-0.05	1.00	Industrial roundwood ³	max	-0.05	1.00
-	min	-1.00	0.00		min	-1.00	0.00
	mean	-0.32	0.67		mean	-0.16	0.56
	SE	0.02	0.03		SE	0.02	0.03
Paper and paperboard ¹	max	-0.05	1.00	Fuelwood ¹	max	-0.05	1.00
	min	-1.00	0.00		min	-1.00	-1.00
	mean	-0.38	0.55		mean	-0.17	0.17
	SE	0.03	0.03		SE	0.02	0.04

Table 1. Summary statistics of country-specific elasticities of domestic demand with respect to price and shifters, byproduct.

¹ Shifter = gross domestic product; ² Shifter = paper and paperboard production; ³ Shifter = sawnwood, wood-based panel, and pulp production.

Table 2. Summary statistics of country-specific elasticity of import demand with respect to product price and shifters, by product.

		Elasticity		D 1 /		Elasticity		
Product		Price	Shifter	- Product -		Price	Shifter	
Sawnwood ¹	max	-0.05	1.00	Wood pulp ²	max	-0.05	1.00	
	min	-1.00	0.00		min	-1.00	0.00	
	mean	-0.39	0.50		mean	-0.17	0.62	
	SE	0.03	0.03		SE	0.02	0.03	
Wood-based panels ¹	max	-0.05	1.00	Industrial roundwood ³	max	-0.05	1.00	
	min	-1.00	0.00		min	-1.00	0.00	
	mean	-0.37	0.75		mean	-0.25	0.28	
	SE	0.03	0.03		SE	0.02	0.03	
Paper and paperboard ¹	max	-0.05	1.00	Fuelwood ¹	max	-0.05	1.00	
	min	-1.00	0.00		min	-1.00	-1.00	
	mean	-0.47	0.63		mean	-0.12	0.15	
	SE	0.03	0.03		SE	0.02	0.04	

¹ Shifter = gross domestic product; ² Shifter = paper and paperboard production; ³ Shifter = sawnwood, wood-based panel, and pulp production.

3.3. Export Supply Parameters

The country- and product-specific marginal propensities to export were obtained by minimizing the sum of squares of the difference between predicted and observed exports, given observed world imports, with the following quadratic program:

Find the parameters $\delta_{ik}^+, \delta_{ik}^-, \theta_{ik}^+, \theta_{ik}^- \ge 0 \ \forall i, k;$

such that:

$$\min SSQR_{ikt} = \sum_{ikt} \left(X_{ikt} - \hat{X}_{ikt} \right)^2 \tag{21}$$

subject to:

$$\hat{X}_{ikt} = \delta_{ik} + \theta_{ik} I_{wkt} \quad \forall i,k$$
(22)

$$\delta_{ik} = \delta^+_{ik} - \delta^-_{ik} \quad \forall i,k \tag{23}$$

$$\theta_{ik} = \theta_{ik}^+ - \theta_{ik}^- \quad \forall i,k \tag{24}$$

Because reported world exports differ from world imports, the estimation was performed by replacing I_{wkt} with $X_{wkt} = \sum_{i=1}^{n} X_{ikt}$. The results summary (Table 3) shows that the mean of the marginal propensity to export (θ_{ik}), across all countries was the same for all products—0.006—while in individual countries it ranged from -0.117 for wood-based panels to 0.386 for wood pulp. All mean values of the marginal propensities to export were statistically significant at least at the 0.01 level.

Product		θ_{ik}	Product		θ_{ik}
Sawnwood	max	0.334	Wood pulp	max	0.386
	min	-0.033		min	-0.044
	mean	0.006		mean	0.006
	SE	0.002		SE	0.002
Wood-based panels	max	0.258	Industrial roundwood	max	0.156
_	min	-0.117		min	-0.064
	mean	0.006		mean	0.006
	SE	0.002		SE	0.002
Paper and paperboard	max	0.181	Fuelwood	max	0.229
	min	-0.077		min	-0.034
	mean	0.006		mean	0.006
	SE	0.002		SE	0.002

Table 3. Summary statistics of country-specific marginal propensity to export (θ_{ik}), by product.

3.4. World Price Parameters

For industrial roundwood, the parameters of the world price equation were estimated with panel data from 180 countries observed from 1992 to 2018, and a linear stochastic version of Equation (9):

$$P_{irt} = \vartheta_{ir} + \mu_r ln Q_{irt} + \pi_r ln S_{it} + \rho_r t + \varepsilon_{irt} \quad \forall i$$
(25)

where P_{irt} was the price of industrial roundwood in country *i* and year *t*, Q_{irt} was the production of industrial roundwood, S_{it} was the forest stock in country *i* and year *t*, and ε_{irt} was a random error. The parameters of Equation (25) were estimated with fixed effects and two-stages least squares ([19] pp. 485–493 and 525–527), with the first stage a regression of production on GDP. The results in Table 4 show that the price of industrial roundwood was positively correlated to its production, negatively correlated to the growing stock, and decreased over time by 1% per year.

Table 4. Parameters of world price equations, by product.

Product	Dependent Variable	Independent Variables	Coef.	SE	
Industrial roundwood	lnP _{irt}	lnQ _{irt}	1.51	0.17	**
		lnS _{it}	-0.38	0.08	**
		t	-0.01	0.00	**
Sawnwood	lnP _{wst}	lnP _{wrt}	0.56	0.10	**
Wood-based panels	lnP _{wlt}	lnP _{wrt}	0.56	0.06	**
Wood pulp	lnP _{wut}	lnP _{wrt}	0.46	0.13	**
Paper and paperboard	lnP _{wat}	lnP _{wut}	0.65	0.10	**
Fuelwood	lnP_{wft}	lnP _{wrt}	0.91	0.19	**

**: statistically significant at 0.01 level.

For sawnwood, wood-based panels, wood pulp, and fuelwood, the world price was estimated by ordinary least squares with a logarithmic form of Equation (10), and timeseries data on world prices from 1992 to 2018. For paper and paperboard a logarithmic form of Equation (11) was used instead. Table 4 shows that the elasticity of the world price of sawnwood, wood-based panels, wood pulp, and fuelwood with respect to the price of industrial roundwood ranged from 0.46 (\pm 0.13) for wood pulp to 0.91 (\pm 0.19) for fuelwood, while the elasticity of the world price of paper and paperboard with the price of wood pulp was 0.65 (\pm 0.10). All elasticities were statistically significant at the 0.01 level.

3.5. Local Price Parameters

The country-specific parameters of Equation (12) were obtained by minimizing the sum of the squares of the differences between the observed and predicted logarithm of local price, given the world price, for all products and countries, from 1992 to 2018:

Find the parameters τ_{ik}^+ , τ_{ik}^- , α_{ik}^+ , $\alpha_{ik}^- \ge 0 \forall i, k$; such that:

$$\min SSQR = \sum_{ikt} \left(lnP_{ikt} - lnP_{wkt} \right)^2$$
(26)

subject to:

$$lnP_{ikt} = \tau_{ik}lnP_{wkt} + \alpha_{ik} \ \forall i,k,t$$
(27)

$$\tau_{ik} = \tau_{ik}^+ - \tau_{ik}^- \quad \forall i,k \tag{28}$$

$$\alpha_{ik} = \alpha_{ik}^+ - \alpha_{ik}^- \quad \forall i, k \tag{29}$$

The results summary (Table 5) shows that the mean price elasticity of the local price with respect to the world price, over all countries, varied from 0.43 for sawnwood to 1.08 for fuelwood. All mean values of the elasticities were statistically significant at least at the 0.01 level.

Table 5. Summary statistics of country-specific elasticity of local price with respect to world price (τ_{ik}) by product.

Product	Ela	asticity	Product	Ela	sticity
Sawnwood	max	4.11	Wood pulp	max	2.33
	min	-3.42		min	-0.85
	mean	0.43		mean	0.88
	SE	0.08		SE	0.03
Wood-based panels	max	3.75	Industrial roundwood	max	2.83
_	min	-3.31		min	-2.14
	mean	1.03		mean	0.81
	SE	0.07		SE	0.06
Paper and paperboard	max	3.11	Fuelwood	max	3.43
	min	-2.16		min	-2.43
	mean	0.83		mean	1.08
	SE	0.05		SE	0.04

3.6. Forest Area Parameters

The parameters of the growth rate of forest area in Equation (14) were estimated by non-linear least squares with cross-sectional data from 186 countries on forest area growth rate and GDP per capita in 2017. With the GDP per capita y_{it} expressed in USD 1000 per person, the linear effect of GDP per capita on the forest growth rate was $\omega = 0.0007$, with a standard error of 0.0001, and the exponential effect was $\vartheta = -0.077$, with a standard error of 0.020—both statistically significant at the 0.01 level.

3.7. Forest Stock Parameters

The country-specific parameters of the forest stock growth–drain Equation (15) were obtained by minimizing the sum of the squares of the difference between the observed and the predicted forest stock, with the following quadratic program:

Find the parameters σ_i^+ , σ_i^- , $\alpha_i \ge 0 \forall i, k$;

such that:

$$\min SSQR_{it} = \sum_{it} \left(S_{it} - \hat{S}_{it}\right)^2 \tag{30}$$

subject to:

$$\hat{S}_{it} = S_{i,t-1}(1+\sigma_i) - \alpha_i(Q_{if,t-1}+Q_{ir,t-1})$$
(31)

$$\sigma_i = \sigma_i^+ - \sigma_i^- \quad \forall i,k \tag{32}$$

$$\alpha_i \le \alpha_i^U \quad \forall i,k \tag{33}$$

where α_i^U is an a priori upper bound on the impact of the harvest on forest growth.

The results in Table 6 show a mean value of the annual growth rate of forest stock without harvest $\overline{\sigma} = 0.009$, and a mean value of the harvest effect $\overline{\alpha} = 0.39$ (with harvest and stock in million m³)—both statistically significant at least at the 0.01 level.

	Growth Rate without Harvest, σ_i	Harvest Effect, α_i
max	0.114	1.20
min	-0.034	0.00
mean	0.009	0.39
SE	0.001	0.03

3.8. Base Year Calibration

The GFPMX formulae automatically calibrate all constant terms in Equations (1)–(14) so that the calculated value in the base year matches the observations in that year. For example, in Equation (1), with base year 2018, the calibrated value of the constant α_{ik} is:

$$\hat{x}_{ik} = C_{ik,2018} P_{ik,2017}^{-\beta_{ik}} Y_{i,2018}^{-\gamma_{ik}} \quad \forall k = f, s, l, a$$
(34)

4. Computer Implementation

The GFPMX software, written by the author, consists of a workbook of multiple spreadsheets in Microsoft Excel[®] (2016). The spreadsheets are macro free. Potential users have control of the basic data for 180 countries. The spreadsheets accommodate 26 years of historical data, currently from 1992 to 2018. The projected years, currently up to 2070, are at the users' discretion, as are the parameters and formulae. Once the program has been uploaded, long-term projections with new data or assumptions are nearly instantaneous. The current version of the GFPMX with the data and parameters described above, and used in the following application to the impact of the COVID-19 pandemic, is available at: https://buongiorno.russell.wisc.edu/gfpm/ (accessed on 5 May 2021). The GFPMX software, data, and model formulation are also available as supplementary material for this paper.

5. Application to the Effect of the COVID-19 Recession on the Global Forest Sector

5.1. Exogenous Projections of the Effect of the COVID-19 on Economic Growth

Table 7 summarizes the International Monetary Fund's projections of GDP growth before the COVID-19 pandemic, published in January 2020 [20], and the revised projections of January 2021 [21]. The projection of the world output for 2020 went from 3.3 percent before the COVID-19 pandemic to -3.5 percent, a contraction of 6.8 percentage points. The contractions for France, Spain, and the United Kingdom exceeded ten percentage points. The growth rates for 2020 were negative for most regions and countries. The only exception was China, projected to grow at 2.3 percent per year in 2020—still less than the pre-COVID-19 projection by 3.7 percentage points. The IMF projections for 2021 suggested a recovery in all countries, but still not enough to compensate for the 2020 contraction. Globally, world output would increase by 5.5 percent in 2021, short of the 6.8% contraction in 2020 relative to the pre-COVID-19 projection.

To estimate the consequences of these projections on the global forest sector, the data in Table 7 were introduced in the GFPMX to simulate two scenarios. A base scenario assumed the pre-COVID-19 growth rates for 2019, 2020, and 2021. The alternative scenario assumed the same GDP growth rates as the base scenario for 2019, and the post-COVID-19 growth rates in Table 7 for 2020 and 2021. To assess the long-term ceteris paribus impact of the COVID-19 recession, the simulations were continued up to the year 2030. In both scenarios the assumed GDP growth from 2022 to 2030, and the assumed population growth from 1999 to 2030, corresponded to the SSP2 scenario—an intermediate scenario among the five demographic and economic scenarios of the Shared Socioeconomic Pathways [22,23].

Table 7. Pre- and post-COVID-2019 International Mor	netary Fund projections of GDP growth in 2020
and 2021.	

	Estimate ²	Proje Pre-CO	ection VID-19 ¹	Proje Post-CO	ction VID-19 ²
Country/Region	2019	2020	2021	2020	2021
World output	2.8	3.3	3.4	-3.5	5.5
Advanced economies	1.6	1.6	1.6	-4.9	4.3
United States	2.2	2	1.7	-3.4	5.1
Euro Area	1.3	1.3	1.4	-7.2	4.2
Germany	0.6	1.1	1.4	-5.4	3.5
France	1.5	1.3	1.3	-9.0	5.5
Italy	0.3	0.5	0.7	-9.2	3.0
Spain	2.0	1.6	1.6	-11.1	5.9
Japan	0.3	0.7	0.5	-5.1	3.1
United Kingdom	1.4	1.4	1.5	-10.0	4.5
Canada	1.9	1.8	1.8	-5.5	3.6
Other advanced economies	1.8	1.9	2.4	-2.5	3.6
Emerging market and developing economies	3.6	4.4	4.6	-2.4	6.3
Emerging and developing Asia	5.4	5.8	5.9	-1.1	8.3
China	6.0	6	5.8	2.3	8.1
India	4.2	5.8	6.5	-8.0	11.5
ASEAN-5	4.9	4.8	5.1	-3.7	5.2
Emerging and developing Europe	2.2	2.6	2.5	-2.8	4.0
Russia	1.3	1.9	2	-3.6	3.0
Latin America and the	0.2	1.6	2.3	-7.4	4.1
Caribbean					
Brazil	1.4	2.2	2.3	-4.5	3.6
Mexico	-0.1	1	1.6	-8.5	4.3
Middle East and Central Asia	1.4	2.8	3.2	-3.2	3.0
Saudi Arabia	0.3	1.9	2.2	-3.9	2.6
Sub-Saharan Africa	3.2	3.5	3.5	-2.6	3.2
Nigeria	2.2	2.5	2.5	-3.2	1.5
South Africa	0.2	0.8	1	-7.5	2.8
¹ IMF 2020; ² IMF 2021.					

5.2. Effects on Roundwood Production and Trade

According to the GFPMX projections, the economic recession due to the COVID-19 pandemic reduced the world production of roundwood (industrial roundwood and fuelwood) by 40.8 million m³ (-1%) in 2020 (Table 8). Despite the projected partial economic recovery in 2021, the world production of roundwood in 2021 was still 19 million m³ less (-0.5%) with the COVID-19 recession than without it. COVID-19's impact increased further to -38 million m³ (-0.9%) by 2030. The largest regional effects were in Europe (-22.8 million m³, or -2.8% in 2020) and in South America (-7.9 million m³, or -2.0%). At the national level, in 2020, production decreased the most in Russia (-7.9 million m³, or -3.3%), India (-3.7 million m³, or -1%), and Brazil (-3.3 million m³, or -1.3%). However, production was higher in the COVID-19 scenario in DR Congo, the United States, and Indonesia.

The world imports of roundwood were 3.9 million m³ lower (-1.7%) in 2020 due to the COVID-19 recession (Table 8). Asia was by far the most affected region, in large part due to lower imports in China (-2.4 million m³, or -2.9% in 2020) and Japan (-793,000 m³, or -3.2%). In 2021, world imports exceeded what they would have been without the

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COVID-19, due mostly to China's imports. But, by 2030 the projected world roundwood imports were still 687,000 m³ less than they would have been without the COVID-19 recession. The effects were nil or negligible on imports in South America, Oceania, and North America.

Table 8. Effect of the COVID-19 economic recession on roundwood production, import, and export in 2020, 2021, and 2030, by region, and in the ten most affected countries in 2020.

Region/	Region/ Production (1000 m ³)		Region/	Import (1000 m ³)			Region/	Exp	ort (1000 n	n ³)	
Country	2020	2021	2030	Country	2020	2021	2030	Country	2020	2021	2030
WORLD ¹	-40,835	-19,231	-37,951	WORLD ¹	-3943	320	-687	WORLD ¹	-4049	353	-710
AFRICA	-5118	-3357	-10,693	AFRICA	-66	-42	-73	AFRICA	-204	0	-53
N. AMERICA	107	532	-306	N. AMERICA	-15	16	0	N. AMERICA	-97	11	-15
S. AMERICA	-7913	-3776	-5814	S. AMERICA	0	0	0	S. AMERICA	-170	28	-16
ASIA	-4131	-3219	-4780	ASIA	-3244	572	-199	ASIA	-367	75	-45
OCEANIA	-985	149	-138	OCEANIA	0	3	0	OCEANIA	-864	138	-84
EUROPE	-22,795	-9560	-16,220	EUROPE	-617	-229	-416	EUROPE	-2345	101	-498
Russia	-7922	-2314	-4757	China	-2431	797	149	Russia	-546	100	-40
India	-3741	-1905	-2265	Japan	-793	-385	-431	Vietnam	-448	73	-42
Brazil	-3302	-1012	-2135	Luxembourg	-133	-15	-50	New Zealand	-423	69	-39
Germany	-2547	-1449	-1918	Italy	-106	-81	-114	Australia	-332	51	-34
Chile	-2434	-1583	-2028	Slovakia	-97	-62	-76	Ukraine	-199	-42	-92
Poland	-1646	-907	-1216	Czech Rep.	-67	-34	-56	Canada	-200	42	-10
Finland	-1516	-853	-1199	South Africa	-59	-38	-55	Latvia	-162	24	-18
Indonesia	1431	1012	872	Austria	-47	-30	-34	Czech Rep.	-132	20	-14
United States	2247	1524	1179	Germany	-28	-12	-15	Thailand	-129	21	-12
Congo, DR	4935	5111	1467	Greece	-24	-16	-21	Malaysia	227	-37	21

¹ World import may differ from world export due to differences in base year statistics.

For exports, the regions most affected by the COVID-19 recession were Europe where exports decreased by 2.3 million m³ (-2.4%) in 2020—and Oceania (-864,000 m³, or -1.7% in 2020). Russia, Vietnam, and New Zealand had the largest national decreases in roundwood exports. The general recovery of 2021 led to global exports that exceeded what they would have been without the COVID-19 recession. Still, by 2030, exports were below what they would have been without the COVID-19, in all regions and countries in Table 8 except Malaysia.

It may be noted that the slight difference between the impact on world imports and exports in Table 8 and succeeding tables is due to differences in world import and export statistics for the base year, here 2018.

5.3. Effects on Sawnwood Production and Trade

The economic recession caused by the COVID-19 pandemic reduced the world production of sawnwood by 8.7 million m³ (1.7%) in 2020 (Table 9). The largest regional reductions were in Europe (-4 million m³, or -2.3%) and Asia (-3.4 million m³, or -2.3%). Among individual countries, sawnwood production was reduced the most in China (-1.9 million m³, or -2%) and Russia (-1.5 million m³, or -3.4%) in 2020. Although the projected partial economic recovery in 2021 reduced the impact of the COVID-19 recession, world sawnwood production was still 4.8 million m³ (0.9%) less in 2021 than it would have been without the COVID-19, and the difference increased further to -7.3 million m³ (-1.2%) by 2030.

In 2020, global world sawnwood imports were projected to be 4.5 million m³ (2.9%) lower due to the COVID-19 recession (Table 9). In absolute terms, imports in Asia were the most affected (-2.6 million m³, or -3.8% in 2020, of which nearly half was in China), followed by the reduction of imports in Europe (-1.2 million m³, or -28%). In 2021 the projected world imports of sawnwood were still 2.4 million m³ less (-1.5%) than

they would have been without the COVID-19 recession—a difference that increased to 3.7 million m^3 (-1.9%) by 2030. In contrast, the consequences of COVID-19 were negligible or small for imports in South America and Oceania.

Table 9. Effect of the COVID-19 economic recession on sawnwood production, import, and export in 2020, 2021, and 2030, by region, and in the ten most affected countries in 2020.

Region/	gion/ Production (1000 m ³)		Region/	Im	port (1000 n	n ³)	Region/	Export (1000 m ³)			
Country	2020	2021	2030	Country	2020	2021	2030	Country	2020	2021	2030
WORLD ¹ AFRICA	-8671 -191	$-4804 \\ -146$	-7253 -252	WORLD ¹ AFRICA	$-4450 \\ -482$	-2369 -452	$-3682 \\ -603$	WORLD ¹ AFRICA	$-4488 \\ -72$	$-2420 \\ -41$	-3795 -87
N. AMERICA	-164	115	-14	N. AMERICA	-155	-82	-120	N. AMERICA	-176	-107	-168
S. AMERICA	-807	-539	-746	S. AMERICA	-30	-22	-30	S. AMERICA	-322	-181	-287
ASIA	-3357	-2095	-2896	ASIA	-2579	-1103	-2007	ASIA	-210	-117	-182
OCEANIA	-147	-82	-125	OCEANIA	-5	$^{-2}$	-4	OCEANIA	-83	-44	-69
EUROPE	-4004	-2056	-3220	EUROPE	-1200	-707	-918	EUROPE	-3626	-1930	-3002
China	-1884	-979	-1222	China	-1207	-211	-482	Russia	-1487	-792	-1231
Russia	-1487	-785	-1226	Japan	-371	-209	-220	Germany	-494	-263	-409
Japan	-555	-313	-331	Egypt	-222	-230	-304	Thailand	-265	-141	-219
Germany	-546	-228	-400	Austria	-172	-106	-119	Ukraine	-192	-102	-158
Vietnam	-498	-492	-933	France	-162	-73	-98	Chile	-182	-97	-151
Chile	-355	-232	-300	Belgium	-156	-111	-154	Sweden	-180	-96	-149
Thailand	-350	-228	-324	Vietnam	-144	-143	-272	Canada	-160	-85	-132
Sweden	-321	-161	-242	Uzbekistan	-139	-23	-175	Latvia	-153	-82	-127
Latvia	-203	-117	-171	Estonia	-129	-92	-108	Belarus	-150	-80	-124
Ukraine	-192	-102	-158	Algeria	-117	-103	-136	Finland	-146	-78	-121

¹ World import differs from world export due to differences in base year statistics.

For sawnwood exports, COVID-19's impact was largest in absolute value in Europe, at -3.6 million m³ (-3.6%) in 2020, reduced to -1.9 million m³ (-1.9%) in 2021, but rising again to -3.0 million m³ (-2.2%) by 2030. At the national level, the largest export losses were in Russia (-1.5 million m³, or -4.5% in 2020) and Germany (Table 9).

5.4. Effects on Wood-Based Panels Production and Trade

Due to the COVID-19 recession, the world production of wood-based panels projected with the GFPMX dropped by 15.5 million m³ (-3.6%) in 2020 compared to what it would have been without the pandemic (Table 10). Despite the partial economic recovery in 2021, world production was still 7.0 million m³ less in 2021 than it would have been with the pre-COVID-19 economic growth projected by the International Monetary Fund. The difference at the global level increased further to -11.5 million m³ (-1.9%) in 2030. The two most affected regions were Asia and Europe, and specifically China (-8.3 million m³, or -4% in 2020) and Russia (-920,000 m³, or -4.9% in 2020).

World imports of wood-based panels were 5.3 million m³ less (-5.4%) in 2020 with the COVID-19 scenario than with the base scenario. In 2021, world production was still 3.0 million m³ less (-3.1%) due to the COVID-19 recession, and the difference increased to -4.5 million m³ (-3.7%) by 2030. Europe, Asia, and North America experienced the largest reductions of imports. The United States was the country with the largest contraction in 2020 (-940,000 m³), but reduced to -291,000 m³ by 2030.

The largest regional impacts of the COVID-19 recession on exports of wood-based panels were in Europe (-3.0 million m³, or -6.4% in 2020)—mostly in Germany and Russia—and in Asia (-1.5 million m³, or -5% in 2020), principally in China (Table 10).

5.5. Effects on Wood Pulp Production and Trade

As summarized in Table 11, the world production of wood pulp was reduced by 3.5 million t (1.9%) in 2020, due to the COVID-19 recession. This reduction was mostly in Asia (-1.4 million t, or -3.5%), South America (-1.0 million t, or -3.6%), and Europe (-1.0 million t, or -2.2%). The countries most affected in absolute terms in 2020 were

Brazil (-704,000 t, or -3.5%), India (-425,000 t, or -12.4%), and Indonesia (-406,000 t, or -4.8%). Although the impact was less in 2021 than in 2020, global wood pulp production was still 2.2 million t less (-1.2%) with the COVID-19 scenario than with the base scenario. Subsequently, this difference increasede, reaching -3.4 million t, or -1.6% in 2030.

Table 10. Effect of the COVID-19 economic recession on wood-based panels production, import, and export in 2020, 2021 and 2030, by region, and in the ten most affected countries in 2020.

Region/	Prod	uction (100	0 m ³)	Region/	Im	port (1000 n	n ³)	Region/	Exp	ort (1000 n	1 ³)
Country	2020	2021	2030	Country	2020	2021	2030	Country	2020	2021	2030
WORLD ¹	-15,475	-6970	-11,502	WORLD ¹	-5288	-3049	-4456	WORLD ¹	-5290	-3053	-4500
AFRICA	-139	-105	-160	AFRICA	-153	-140	-207	AFRICA	-33	-19	-30
N. AMERICA	224	29	-99	N. AMERICA	-1319	-449	-656	N. AMERICA	-235	-136	-199
S. AMERICA	-1293	-751	-1094	S. AMERICA	-183	-152	-200	S. AMERICA	-398	-230	-346
ASIA	-10,207	-3721	-6728	ASIA	-1373	-957	-1599	ASIA	-1540	-889	-1326
OCEANIA	-104	-53	-76	OCEANIA	-36	-20	-29	OCEANIA	-50	-29	-43
EUROPE	-3956	-2368	-3345	EUROPE	-2224	-1332	-1764	EUROPE	-3034	-1749	-2556
China	-8323	-2329	-4507	United States	-940	-173	-291	China	-1364	-787	-1149
Russia	-920	-604	-791	Germany	-319	-187	-203	Germany	-512	-295	-431
Brazil	-724	-335	-523	France	-255	-133	-191	Thailand	-419	-242	-353
Poland	-693	-399	-570	Italy	-267	-177	-256	Russia	-391	-225	-329
Thailand	-571	-372	-528	Canada	-219	-153	-201	Canada	-329	-190	-277
Turkey	-552	-395	-532	Poland	-203	-115	-163	Belgium	-263	-152	-222
Canada	-547	-366	-483	Japan	-170	-80	-88	Poland	-248	-143	-209
India	-452	-335	-651	Belgium	-136	-74	-111	Brazil	-224	-129	-188
Chile	-293	-215	-284	India	-137	-94	-186	Romania	-215	-124	-181
Belarus	-252	-150	-208	Mexico	-125	-95	-129	Indonesia	621	358	523

¹ World import differs from world export due to differences in base year statistics.

Table 11. Effect of the COVID-19 economic recession on wood pulp production, import, and export in 2020, 2021, and 2030, by region and in the ten most affected countries in 2020.

	Production (1000 t)			р · /	Import (1000 t)			Region/	Export (1000 t)		
Country	11000000		_ Region/								
	2020	2021	2030	Country	2020	2021	2030	Country	2020	2021	2030
WORLD ¹	-3524	-2244	-3350	WORLD ¹	-1332	-587	-958	WORLD ¹	-1331	-587	-978
AFRICA	-2	-8	$^{-2}$	AFRICA	$^{-8}$	-4	-16	AFRICA	19	8	4
N. AMERICA	-65	45	4	N. AMERICA	-96	-49	-78	N. AMERICA	-27	-12	-20
S. AMERICA	-1024	-518	-774	S. AMERICA	-24	-17	-22	S. AMERICA	-789	-348	-567
ASIA	-1379	-1087	-1583	ASIA	-769	-227	-442	ASIA	-198	-88	-143
OCEANIA	-31	-19	-26	OCEANIA	-7	-3	-6	OCEANIA	-13	-6	-9
EUROPE	-1023	-657	-970	EUROPE	-427	-287	-394	EUROPE	-322	-142	-242
Brazil	-704	-365	-537	China	-466	-11	-112	Brazil	-515	-227	-370
India	-425	-309	-603	India	-105	-76	-141	Chile	-161	-71	-116
Indonesia	-406	-279	-399	Belgium	-106	-79	-105	Indonesia	-156	-69	-112
Russia	-311	-204	-271	Germany	-92	-62	-82	Uruguay	-113	-50	-81
United States	-281	-104	-210	Mexico	-82	-60	-81	United States	-87	-38	-62
China	-242	-272	-267	Poland	-73	-52	-71	Finland	-86	-38	-62
Finland	-220	-134	-199	Spain	-56	-39	-50	Russia	-58	-26	-42
Chile	-189	-91	-141	Italy	-44	-26	-32	Germany	-49	-22	-35
Sweden	-133	-92	-125	Turkey	-41	-30	-37	Netherlands	-47	-21	-34
Canada	236	165	237	Korea, Rep.	-38	-25	-30	Canada	59	26	43

¹ World import differs from world export due to differences in base year statistics.

In the COVID-19 recession scenario, the world imports of wood pulp were 1.3 million t, or 2.3% less in 2020 than in the base scenario. Despite the 2021 recovery, imports were still 587,000 t (1.5%) less in 2021, and 958,000 t less in 2030. The largest decreases of imports in

2020 were in Asia (-769,000 t, or -2.4%) and Europe (-427,000 t, or -2.3%). China, India, and Belgium were the countries with the largest reductions of imports.

Exports of wood pulp were reduced the most in South America (-789,000 t, or -3.8% in 2020), Europe (-322,000 t, or -2.1%), and Asia (-198,000 t, or -3.8%). For individual countries, the largest national reductions of exports in 2020 were in Brazil (-515,000 t, or -3.7%), Chile (-161,000 t, or -3.6%), and Indonesia (-156,000 t, or -4.1%).

5.6. Effects on Paper and Paperboard Production and Trade

According to the GFPMX simulations, the economic recession caused by the COVID-19 pandemic reduced world production of paper and paperboard by 11.8 million t (-2.8%) in 2020 (Table 12). Although the economic recovery projected in 2021 narrowed the difference, wood pulp production was still 8.0 million t less (-1.9%) in the COVID-19 scenario, and the difference increased to 12 million t (-2.3%) by 2030. The two most affected regions were Asia (-7.4 million t, or -3.6% in 2020), and Europe (-3.3 million t, or -3.1%). At the national level, China's production was reduced the most due to the COVID-19 recession (-2.6 million t, or -2.2% in 2020), followed by India (-2.4 million t, or -12.4%) and Germany (-887,000 t, or -3.9%).

Table 12. Effect of the COVID-19 economic recession on paper and paperboard production, import, and export in 2020, 2021, and 2030, by region, and in the ten most affected countries in 2020.

Region/	Production (1000 t)			Region/	Import (1000 t)			Region/	Export (1000 t)		
Country	2020	2021	2030	Country	2020	2021	2030	Country	2020	2021	2030
WORLD ¹	-11,761	-7966	-11,809	WORLD ¹	-4753	-3395	-4753	WORLD ¹	-4751	-3394	-4763
AFRICA	-46	-37	-64	AFRICA	-310	-282	-394	AFRICA	-44	-32	-45
N. AMERICA	-464	-337	-478	N. AMERICA	-584	-419	-557	N. AMERICA	24	17	23
S. AMERICA	-531	-397	-492	S. AMERICA	-185	-147	-180	S. AMERICA	-144	-103	-154
ASIA	-7362	-4761	-7426	ASIA	-1503	-1186	-1901	ASIA	-1273	-910	-1274
OCEANIA	-84	-62	-86	OCEANIA	-21	-10	-13	OCEANIA	-90	-64	-90
EUROPE	-3275	-2373	-3262	EUROPE	-2151	-1350	-1707	EUROPE	-3223	-2302	-3223
China	-2625	-1135	-1531	India	-465	-324	-640	Germany	-859	-613	-859
India	-2366	-1728	-3355	Mexico	-391	-280	-384	Belgium	-370	-265	-370
Germany	-887	-633	-878	Germany	-344	-174	-199	China	-358	-256	-358
Indonesia	-670	-572	-807	Italy	-333	-231	-296	United States	-319	-228	-319
Mexico	-539	-403	-548	Belgium	-284	-176	-254	Indonesia	-318	-227	-318
Thailand	-383	-345	-445	Poland	-232	-166	-217	Sweden	-305	-218	-306
Japan	-379	-220	-239	Turkey	-151	-108	-146	Korea, Rep.	-217	-155	-217
Korea, Rep.	-378	-267	-332	Spain	-148	-93	-106	Spain	-213	-152	-213
Russia	-345	-248	-317	Vietnam	-147	-142	-273	Finland	-209	-150	-209
Canada	437	317	425	Thailand	-92	-94	-120	Canada	365	261	365

¹ World import differs from world export due to differences in base year statistics.

The COVID-19 recession, led to a drop in world imports of paper and paperboard of 4.8 million t (-4.1%) in 2020. With the 2021 recovery this difference was reduced to -3.4 million t (-2.9%), but it then increased progressively to reach -4.8 million t (-3.4%) in 2030. Like production, imports decreased the most in Europe (-2.2 million t, or -4% in 2020) and in Asia (-1.5 million t, or -4.5%). India was the most affected individual country (-465,000 t, or -13%) in 2020, followed by Mexico (-391,000 t, or -9.4%) and Germany (-344,000 t, or -3.1%).

On the export side, the largest absolute changes were also in Asia and Europe. In Europe, exports of paper and paperboard were 3.2 million t less (-4.6%) in 2020 in the COVID-19 scenario than in the base scenario. Although the 2021 recovery reduced the difference to -2.3 million t, it subsequently increased to reach -3.2 million t (-3.8%) in 2030. In Asia, exports were 1.3 million t less (-5.5%) in 2020, 910,000 t less in 2021, and

1.3 million t less in 2030. The most affected countries were Germany—where exports of paper and paperboard were 859,000 t (-5.9%) lower in 2020 in the COVID-19 scenario—Belgium (-370,000 t, or -10.3%), and China (-358,000 t, or -5.3%).

5.7. Effects on Price and Value Added

Figure 1 shows the effects of the recession induced by the COVID-19 pandemic on the world prices of forest products. In accordance with the cobweb theorem, the projected prices adjusted to the 2020 and 2021 disturbances according to an oscillating pattern, converging to a long-term equilibrium. The largest relative impact was on the price of roundwood, which was 2.3 percent lower in 2020 with the COVID-19 scenario than with the base scenario. Due to the partial economic recovery, the difference reduced to -1% in 2021, and then stabilized at -1.4% by 2025. The least affected commodity was paper and paperboard, for which the price was only 0.7% lower in 2020 with the COVID-19 scenario—a difference that converged towards -0.4% by 2022–2023.



Figure 1. Dynamic adjustment of the world price of forest products to the COVID-19 economic recession, from 2019 to 2030.

Table 13 shows the combined effects of the price changes and the changes in production and consumption of the various products on the value added generated in industries, by region, and in the countries most affected by the COVID-19 recession. Here, value added was defined as the value of sawnwood, wood-based panels, wood pulp, and paper and paperboard, minus the cost of the wood products used in making them: industrial roundwood and wood pulp. The results in Table 13 show that, at the global level, the value added was USD 18.5 billion (3.8%) lower in 2020 due to the recession induced by the COVID-19 pandemic. After the 2021 recovery the difference was reduced to USD -10.7 billion (-2.2%), but it then increased again to reach USD -17.4 billion (-2.6%) in 2030. Regionally, value added was most affected in Asia (USD -12.4 billion, or -4.9%in 2020), and principally in China (USD -7.2 billion, or -4% in 2020) and India (USD -1.9 billion, or -32% in 2020). In contrast, the impact was negligible in North America.

	202	0	202	21	2030		
Region/Country	Million USD	%	Million USD	%	Million USD	%	
WORLD	-18,510	-3.8	-10,681	-2.2	-17,443	-2.6	
AFRICA	-70	-2.6	-80	-3.0	-125	-3.5	
N. AMERICA	-318	-0.4	-285	-0.4	-413	-0.5	
S. AMERICA	-1044	-4.4	-665	-2.7	-941	-3.2	
ASIA	-12,402	-4.9	-6521	-2.4	-11,444	-2.8	
OCEANIA	-171	-2.7	-104	-1.6	-155	-2.1	
EUROPE	-4505	-3.7	-3026	-2.5	-4364	-3.0	
China	-7230	-4.0	-2802	-1.5	-5148	-1.7	
India	-1895	-32.2	-1358	-20.1	-2747	-13.1	
Germany	-1234	-4.3	-767	-2.6	-1173	-3.3	
Japan	-698	-2.8	-380	-1.5	-455	-1.7	
Brazil	-695	-4.3	-409	-2.5	-598	-3.0	
Indonesia	-652	-5.3	-454	-3.6	-667	-4.0	
Thailand	-586	-9.1	-436	-6.5	-638	-6.8	
Vietnam	-430	-9.5	-389	-8.2	-778	-8.4	
Mexico	-406	-11.5	-304	-8.4	-419	-8.2	
Korea, Rep.	-338	-4.2	-208	-2.5	-285	-3.1	

Table 13. Effect of the COVID-19 economic recession on the value added in forest industries in 2020 and 2021, by region, and in the ten most affected countries in 2020.

6. Summary and Conclusions

The first part of this paper presented the GFPMX—a model of the global forest sector anchored on the cobweb theorem. In this view, instead of consisting of a succession of perfect equilibria, a dynamic economy constantly seeks an equilibrium, typically in oscillating patterns, without necessarily reaching it. The model assumes that demand creates its own supply. Consequently, domestic and import demand are the drivers in the evolution of the global forest sector, and global import demand induces export supply. Domestic production then fills the net demand: consumption minus imports plus exports. Local prices depend on the world price. The world price is a function of production, the price of inputs, and the level of forest growing stock. Forest area changes according to a Kuznets environmental curve, while forest stock is projected via a growth–drain process.

The parameters of the GFPMX were estimated with data from the FAO production and trade statistics, the World Bank indicators, and the FAO Forest Resources Assessment. The domestic and import demand elasticities, as well as the export supply parameters, the local price parameters, and the forest stock parameters, were country-specific, estimated by quadratic programming with time-series data from 1992 to 2018.

The GFPMX was implemented as a workbook of Excel[©] spreadsheets. The spreadsheet formulae automatically calibrate the GFPMX to replicate the base year data of 2018, and then project the consumption, imports, exports, production, and prices of six commodity groups, as well as forest area and forest stock, conditional on projections of GNP, population, and tariffs.

The model was applied to project the consequences of the COVID-19 recession on the global forest sector. The base scenario, without COVID-19, and the alternative scenario, with COVID-19, differed according to the Internal Monetary Fund's projections of GDP for 2020 and 2021 before the COVID-19 pandemic, and the revised projections published in January 2021, after the pandemic. The difference between the two scenarios showed the short-term impact of the COVID-19 recession on the forest sector in 2020 and 2021, and its long-term consequences up to 2030. The variables considered were production, imports, exports, and the world prices of roundwood, sawnwood, wood-based panels, wood pulp, and paper and paperboard. The results exhibited dampened oscillation patterns converging towards an equilibrium, consistent with the cobweb theorem.

Globally, the GFPMX projected that the world production of the combined forest industries was USD 34.6 billion (2.7%) lower in 2020 than it would have been without the COVID-19 recession. Despite a projected partial recovery in 2021, the difference was still USD -31.8 billion in 2030. The world trade of forest products in 2020 was USD 11.1 billion lower (-4.5%) with the COVID-19 scenario than without it. Although the difference reduced to USD -6.1 billion (-2.4%) in 2021, it still reached USD -9.6 billion (-3.1%) by 2030.

Since there appear to be few applications of the cobweb theorem to forest sector models—or to other economic sector models for that matter—a useful future area of inquiry could be a comparison of this type of model with, for example, partial equilibrium models [24], in terms of their forecasting accuracy, difficulty of implementation, and cost of application. Meanwhile, as a readily available open source software, with transparent data and formulae depending only on the Excel© program, and nearly instantaneous calculations once the software has been uploaded, the GFPMX should be a useful tool for the investigation of other forest sector economic and policy issues of national, regional, and international scope, such as lumber dispute issues and other trade matters [25].

Supplementary Materials: The following are available online at https://www.mdpi.com/article/1 0.3390/su13105507/s1, GFPMX software, data, and formulation.

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