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

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**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. The paper presents the model 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

## 1. Introduction

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

Unlike other forest sector models (Adams et al., 1996; Buongiorno et al., 2003; Kallio et al., 2004; Lauri et al., 2013) that use partial equilibrium theory (Samuelson, 1952; Takayama and Judge 1971), the GFPMX relies on the Cobweb theorem (Ezekiel 1938, Pashigian 2008, Waugh 1964). In this view, instead of following a succession of perfect equilibria, a dynamic economy tends to only converge gradually towards an equilibrium in typically oscillating patterns, without necessarily reaching it.

The proposed model also assumes that demand creates its own supply (Krugman, 2015; in contrast with Say's law (Say, 1834)). Thus, in 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 (Dinda, 2004), while forest stock varies according to a growth-drain equation (Mills, 1989).

The first part of the 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, 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" (Chudik et al. 2020). 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, global production of forest industries was nearly \$35 billion less (-2.7%) in 2020 and still \$32 billion less in 2030, and 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.

*Domestic demand of end products*

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

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

$C_{ikt}$= 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

*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:

$$C_{iut} = \alpha_{iu} P_{iu,t-1}^{\beta_{iu}} Q_{iat}^{\gamma_{iu}} \tag{2}$$

$C_{iut}$= 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.

*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:

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

$C_{irt}$= 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,
$\alpha_{ir}, \beta_{ir}, \gamma_{ir}$= 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.

*Import demand for fuelwood, sawnwood, panels, paper and paperboard*

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

$I_{ikt}$= 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,

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

*Import demand for wood pulp*

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

$I_{iut}$= 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.

*Import demand for industrial roundwood*

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

$I_{irt}$= 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,
$\alpha_{ir}, \beta_{ir}, \gamma_{ir}$= country-specific parameters.

*Export supply*

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

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

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

*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:

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

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

*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 a time trend:

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

$P_{wrt}$=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,
$\vartheta_r, \mu_r, \pi_r, \rho_r$= parameters.

*World price of fuelwood, sawnwood, wood pulp, and wood-based panels:*

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

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

$P_{wkt}$=world price of product $k$ in year $t$,
$P_{wrt}$=world price of industrial roundwood in year $t$,
$\vartheta_k, \mu_k, \pi_k, \rho_k$= parameters.

*World price of paper+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 $t$,
$\vartheta_a, \mu_a, \pi_a, \rho_a$= parameters.

*Local price:*

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

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

$P_{ik,t}$ = price of product $k$ in country $i$ and year $t$,
$P_{wk,t}$ = world price of product $k$ in country $i$ and year $t$.
$\sigma_{ik}, \tau_{ik}$= parameters.

*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 $t$,
$\varphi_i$= country-specific constant,
$\omega, \vartheta$ = 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.

*Forest stock:*

The forest stock in each country changes over time according to the following growth-drain equation:

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

$S_{it}$ =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 $i$,
$\sigma_i$ = 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

*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 (2019). The data on population and real GDP, in constant United States dollars, and the data on the United States GDP deflator came from the World Bank data base (WBI, 2019). 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 (FAO 2020).

*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 consumption, or imports, given the local price and demand shifter, for all products and countries, conditional on a-priori upper and lower bounds on the elasticities. For example, country and product specific parameters of the domestic demand equation 1 were obtained by solving the following quadratic program (Buongiorno, 2019):

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

Such that:

$$\min SSQR = \sum_{ikt} (lnC_{ikt} - \widehat{lnC_{ikt}})^2 \qquad (16)$$

Subject to:

$$\widehat{lnC_{ikt}} = \beta_{ik} lnP_{ik,t-1} + \gamma_{ik} lnY_{ikt} + \alpha_{ik} \quad \forall i, k \qquad (17)$$

$$\beta_{ik}^{L} \leq \beta_{ik} = \beta_{ik}^{+} - \beta_{ik}^{-} \leq \beta_{ik}^{U} \quad \forall i, k \qquad (18)$$

$$\gamma_{ik}^{L} \leq \gamma_{ik} = \gamma_{ik}^{+} - \gamma_{ik}^{-} \leq \gamma_{ik}^{U} \quad \forall i, k \qquad (19)$$

$$\alpha_{ik} = \alpha_{ik}^{+} - \alpha_{ik}^{-} \quad \forall i, k \qquad (20)$$

Where the superscripts $L$ and $U$ in equations 18–19 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, panels, and pulp production was 0.56. All mean values of the elasticities were statistically significant at least at the 0.01 level.

**Table 1.** Summary statistics of country-specific elasticities of *domestic demand* with respect to price and shifter, by product.

| | | Elasticity | | | | 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+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 |

[1]Shifter = Gross domestic product,
[2]Shifter = paper + paperboard production,
[3]Shifter = sawnwood + panels + pulp production.

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.

**Table 2.** Summary statistics of country-specific elasticities of *import demand* with respect to product price and shifter, by product.

| Product | | Elasticity Price | Elasticity Shifter | Product | | Elasticity Price | Elasticity 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+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 + paperboard production,
[3]Shifter=sawnwood + panels + pulp production.

*Export supply parameters:*

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

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

Such that:

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

Subject to:

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

$$\delta_{ik} = \delta_{ik}^{+} - \delta_{ik}^{-} \qquad \forall i,k \qquad (23)$$

$$\theta_{ik} = \theta_{ik}^{+} - \theta_{ik}^{-} \qquad \forall i,k \qquad (24)$$

Because reported world exports differ from world imports, the estimation was done by replacing $I_{wkt}$ by $X_{wkt} = \sum_{i=1}^{n} X_{ikt}$ . The results summary (Table 3) show that the mean marginal propensity to export across all countries $\theta_{ik}$ 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.

**Table 3.** Summary statistics of country-specific marginal propensities to *export*, $\theta$, by product.

| **Product** | | $\boldsymbol{\theta}$ | **Product** | | $\boldsymbol{\theta}$ |
|---|---|---|---|---|---|
| **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+paper-board | 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 |

*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 with a linear stochastic version of Equation 9:

$$P_{irt} = \vartheta_{ir} + \mu_r lnQ_{irt} + \pi_r lnS_{it} + \rho_r t + \varepsilon_{irt} \qquad \forall i \qquad (25)$$

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 $\varepsilon_{irt}$ was a random error. The parameters of Equation 25 were estimated with fixed-effects (Wooldridge, 2006 p. 485-493). The results in Table 4 show that the price of industrial roundwood was positively related to the production, negatively to the growing stock, and decreased over time at 1% per year.

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

| **Product** | **Dependent variable** | **Independent variables** | **Coef.** | **SE** | |
|---|---|---|---|---|---|
| Industrial roundwood | $lnP_{wrt}$ | $lnQ_{wrt}$ | 1.51 | 0.17 | ** |
| | | $lnS_t$ | -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+paper-board | $lnP_{wat}$ | $lnP_{wut}$ | 0.65 | 0.10 | ** |

| | | | | | |
|---|---|---|---|---|---|
| Fuelwood | $lnP_{wft}$ | $lnP_{wrt}$ | 0.91 | 0.19 | ** |

**,*: statistically significant at 0.01 level.

For fuelwood, sawnwood, wood-based panels, wood pulp, and fuelwood, the world price was estimated with a logarithmic form of equation 10, with time-series data on world prices from 1992 to 2018. For paper and paperboard a linear version 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(±0.13) for wood pulp to 0.91(±0.19) for fuelwood, while the elasticity of the world price of paper and paperboard with the price of wood pulp was 0.65(±0.10).

*Local price parameters:*

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

Find the parameters. $\tau_{ik}^{+}, \tau_{ik}^{-}, \alpha_{ik}^{+}, \alpha_{ik}^{-} \geq 0\ \forall i, k$

Such that:

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

Subject to:

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

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

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

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 elasticities of *local price* with respect to world price, $\tau$ ,by product.

| Product | Elasticity | | Product | Elasticity | |
|---|---|---|---|---|---|
| **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+paper-board | 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 |

*Forest area parameters*

The parameters of the equation for the growth rate of forest area [13] 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 $1000

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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.

*Forest stock parameters*

The country-specific parameters of the forest stock growth-drain equation 15 were obtained with the following quadratic program:

Find the parameters $\sigma_i^+, \sigma_i^-, \alpha_i \geq 0 \;\; \forall i, k$.

Such that:

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

Subject to:

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

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

$$\alpha_i \leq \alpha_i^U \qquad \forall i, k \tag{30}$$

Where $\alpha_i^U$ 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 $\bar{\sigma}$=0.009 and a mean value of the harvest effect $\bar{\alpha}$=0.39 (with harvest and stock in million m³), both statistically significant at least at the 0.01 level.

**Table 6.** Summary statistics of country-specific *stock growth* parameters.

| | Growth rate without harvest, $\sigma_i$ | Harvest effect, $\alpha_i$ |
|---|---|---|
| max | 0.114 | 1.20 |
| min | -0.034 | 0.00 |
| mean | 0.009 | 0.39 |
| SE | 0.001 | 0.03 |

*Base year calibration*

The GFPMX formulas calibrate automatically all constant terms in the 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 $\alpha_{ik}$is:

$$\hat{\alpha}_{ik} = C_{ik,2018} P_{ik,2017}^{-\beta_{ik}} Y_{i,2018}^{-\gamma_{ik}} \qquad \forall k = f, s, l, a \tag{31}$$

## 4. Computer Implementation

The GFPMX software consists of a workbook of multiple spreadsheets in Excel®, without macros. Potential users have control of the basic data for 180 countries. The program accommodates 26 years of historical data, currently from 1992 to 2018. The projected years, currently up to 2070, are at users' discretion, as are the parameters and formulas. 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/

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

*Exogenous projections of the effect of the COVID-19 on economic growth*

Table 7 summarizes the International Monetary Fund projections of the GDP growth before the COVID-19 pandemic, published in January, 2020 (IMF 2020), and the revised projections of January, 2021 (IMF 2021). The projection of the world output for 2020 went from 3.3 percent before the COVID-19 to -3.5 percent, a contraction of 6.8 percentage points. The contraction 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.

**Table 7.** Pre and post COVID-2019 International Monetary fund projections of GDP growth in 2020 and 2021.

| | Estimate[2] | Projection Pre COVID-19[1] | | Projection Post COVID-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 Caribbean | 0.2 | 1.6 | 2.3 | -7.4 | 4.1 |
| 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.

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 with the same annual GDP growth for the base scenario and for the alternative from 2022 to 2030. The assumed GDP growth from 2022 to 2030, and the assumed population growth rates from 1999 to 2030 corresponded to the SSP2 scenario, an intermediate scenario among the five demographic and economic scenarios of the Shared Socioeconomic Pathways (Dellink et al., 2017; KC and Lutz, 2017).

*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+fuelwood) by 40.8 million m$^3$ (-1%) in 2020 (Table 8). Despite the projected partial economic recovery in 2021, the world production of roundwood in 2021 was still 19 million m$^3$ less (-0.5%) with the COVID-19 recession than without it. The COVID-19 impact increased further to -37.8 million m$^3$ (-0.9%) by 2030. The largest regional effects were in Europe (-22.8 million m$^3$, or -2.8% in 2020) and in South America (-7.9 million m$^3$, or -2.0%). At country level, in 2020, production decreased most in Russia (-7.9 million m$^3$ or -3.3%), India (-3.7 million m$^3$ or -1%), and Brazil (-3.3 million m$^3$ or -1.3%). However, production was higher with the COVID-19 scenario in the Congo DR, the United States and Indonesia.

**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/ | Production (1000 m$^3$) | | | Region/ | Import (1000 m$^3$) | | | Region/ | Export (1000 m$^3$) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| country | 2020 | 2021 | 2030 | country | 2020 | 2021 | 2030 | country | 2020 | 2021 | 2030 |
| WORLD[1] | -40835 | -19231 | -37951 | WORLD[1] | -3943 | 320 | -687 | WORLD[1] | -4049 | 353 | -710 |
| AFRICA | -5118 | -3357 | -10693 | 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 | -22795 | -9560 | -16220 | 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 | Viet Nam | -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.

The world imports of roundwood were 3.9 million m$^3$ 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 m$^3$ or -2.9% in 2020) and Japan (-793,000 m$^3$ or -3.2%). In 2021 world imports exceeded what they would have been without the recovery, 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, Africa, and North America.

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 in Oceania (-864,000 m³ or -1.7% in 2020). Russia, Viet Nam, 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 with the COVID-19 impact, 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 was due to differences in world import and export statistics for the base year, here 2018.

*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%) (Table 9). The largest regional reduction was in Europe (-4 million m³, or -2.3%), and Asia (-3.4 million m³ or -2.3%) in 2020. 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, the world sawnwood production was still 4.8 million m³ or 0.9% less in 2021 than it would have been without the COVID-19, and the difference increased further to -7.2 million m³ (-1.2%) by 2030.

**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/country | Production (1000 m³) | | | Region/country | Import (1000 m³) | | | Region/country | Export (1000 m³) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2020 | 2021 | 2030 | | 2020 | 2021 | 2030 | | 2020 | 2021 | 2030 |
| WORLD[1] | -8671 | -4804 | -7253 | WORLD[1] | -4450 | -2369 | -3682 | WORLD[1] | -4488 | -2420 | -3795 |
| AFRICA | -191 | -146 | -252 | AFRICA | -482 | -452 | -603 | AFRICA | -72 | -41 | -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 |
| Viet Nam | -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 | Viet Nam | -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.

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 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 m³ (-1.9%) by 2030. In contrast, the COVID-19 consequences were negligible or small for imports in South America, North America, and Oceania.

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

*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, the 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 world 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).

**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/country | Production (1000 m³) | | | Region/country | Import (1000 m³) | | | Region/country | Export (1000 m³) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2020 | 2021 | 2030 | | 2020 | 2021 | 2030 | | 2020 | 2021 | 2030 |
| WORLD[1] | -15475 | -6970 | -11502 | 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 | -10207 | -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.

World imports of wood-based panels were 5.3 million m³ less (-5.4%) in 2020 with the COVID-19 scenario than in 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 drops 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, -5% in 2020), principally in China (Table 10).

*Effects on wood pulp production and trade*

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As summarized in Table 11, the world production of wood pulp was reduced by 3.5 million t, or 1.9% in 2020, due to 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 were Brazil (-704,000 t, or -3.5%) in 2020, 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, the world 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 increased over time, reaching -3.4 million t, or -1.6% in 2030.

**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.

| Region/country | Production (1000t) | | | Region/country | Import (1000t) | | | Region/country | Export (1000t) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2020 | 2021 | 2030 | | 2020 | 2021 | 2030 | | 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.

With the COVID-19 recession scenario, the world imports of wood pulp were 1.3 million t, or 2.3% less in 2020 than with the base scenario. Despite the 2021 recovery, imports were still 587,000 t, or 1.5% less in 2021, and 958,000t 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 decrease of imports.

Exports of wood pulp were reduced 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%).

*Effects on paper+paperboard production and trade*

According to the GPMX simulations, the economic recession effected 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%) with 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 country 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+paperboard* production, import, and export in 2020, 2021, and 2030, by region and the ten most affected countries in 2020.

| Region/country | Production (1000t) | | | Region/country | Import (1000t) | | | Region/country | Export (1000t) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2020 | 2021 | 2030 | | 2020 | 2021 | 2030 | | 2020 | 2021 | 2030 |
| WORLD[1] | -11761 | -7966 | -11809 | 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 | Viet Nam | -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 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 with the COVID-19 scenario than with 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 with the COVID-19, Belgium (-370,000 t, or -10.3%), and China (-358,000 t, or -5.3%).

*Effects on price and value added*

Figure 1 shows the effect of the recession induced by the COVID-19 pandemic on the world price of forest products. In accord 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 without it. Due to the partial economic recovery the difference reduced to -1 percent in 2021, and then stabilized to -1.4% by 2025. The least affected commodity was paper+paperboard, for which the price was only 0.7% lower in 2020 in the COVID-19 scenario, a difference that converged towards -0.4% by 2022-2023.

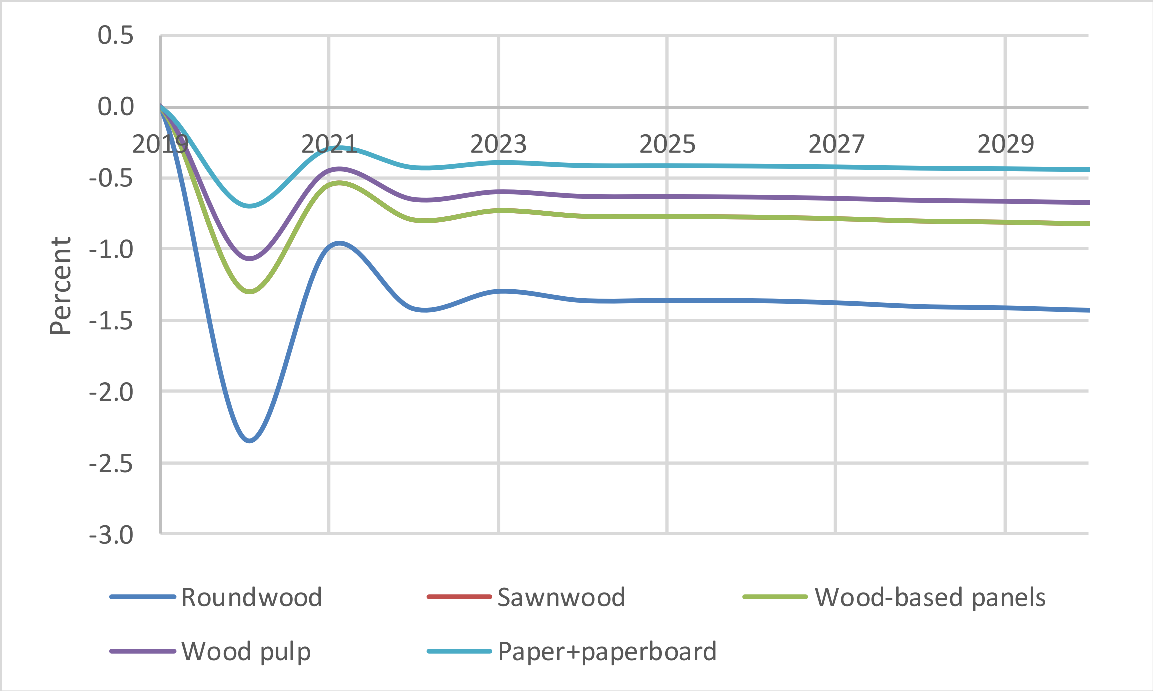


**Figure 1.** Dynamic adjustment of the *world price* of forest products to the COVID-19 economic recession, from 2019 to 2030.

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 by industries in world regions and countries most affected by the COVID-19 recession. Here, value added was defined as the value of sawnwood, panels, wood pulp, and paper+paperboard, minus the cost of the wood products used in making them: industrial roundwood and wood pulp. The results in Table 14 show that at world level, value added was $18.5 billion (-3.8%) lower in 2020 due to the recession induced by the COVID 19. After the 2021 recovery the difference was reduced to -$10.7 billion (-2.2%), but it then increased again to reach $-17.4 billion (-2.6%) in 2030. Regionally, value added was most affected in Asia (-$12.4 billion, or -4.9% in 2020), and principally in China (-$7.2 billion, or -4% in 2020), and in India (-$1.9 billion or -32% in 2020). In contrast, the impact was negligible in North America, Oceania, and Africa.

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

| Region/country | **2020** | | 2021 | | 2030 | |
|---|---|---|---|---|---|---|
| | **Million $** | % | Million $ | % | Million $ | % |
| WORLD | -18510 | -3.8 | -10681 | -2.2 | -17443 | -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 | -12402 | -4.9 | -6521 | -2.4 | -11444 | -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 |
| Viet Nam | -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 |

## 7. Summary and Conclusion

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 seeks constantly an equilibrium in typically 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 with 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 formulas 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 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 world prices of roundwood, sawnwood, wood-based panels, wood pulp, and paper and paperboard. The results exhibited the 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 $34.6 billion or -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 -$31.8 billion in 2030. The world trade of forest products in 2020 was $11.1 billion lower (-4.5%) with the COVID-19 scenario than without it. Although the difference reduced to -$6.1 billion or -2.4% in 2021, it still reached -9.6 billion or -3.1% by 2030.

As a readily available open source software, with transparent data and formulas depending only on the Excel© program, and nearly instantaneous calculations once the software has been uploaded, the GFPMX should be a useful tool to investigate other forest sector economic and policy issues of national, regional, and international scope.

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