

Global modelling to predict timber production and prices: the GFPM approach

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Timber production and prices are determined by the global demand for forest products, and the capability of producers from many countries to grow and harvest trees, transform them into products and export. The Global Forest Products Model (GFPM) simulates how this global demand and supply of multiple products among many countries determines prices and attendant consumption, production and trade. This paper documents the methods, data and computer software of the GFPM model, followed by examples of applications to forecasting, and for policy analysis of the consequences of offset payments for carbon sequestration in forests.

Introduction

As an economic entity, the global forest sector consists of all the activities related to the growing and harvesting of wood in forests, to the transportation and transformation of this wood in forest industries and to the utilization of the resulting products in downstream activities. Like the rest of the economy, the forest sectors of different countries are highly integrated due to active international investments and trade. For example, foreign direct investment between the European Union and the US is intense (EC-Trade, 2013). And, China's rapid economic growth has had large effects on the forest economy of Asia Pacific countries and of the US through wood imports and exports of processed products (Katsigris *et al.*, 2005).

This global interconnection of markets implies that the forest product prices and the attendant production, consumption and trade in any country are to a large extent determined by the world demand and supply rather than by the conditions of each individual country. This is of importance in all decision making, and it is especially critical for long-term investments, such as the development of planted forests or investments in new pulp and paper mills.

Long-term market conditions are also affected by policy. New trade agreements such as the proposed transatlantic trade and investment partnership (Felbermayr *et al.*, 2013), and the progressive introduction of offset payments for carbon sequestration in forests (World Bank, 2011), have an impact of forest area and volume, wood harvest and forest industries.

It is therefore apparent that long-term forest planning in the forest economy requires proper tools to predict if not the exact level, at least the general future trend of global timber production and prices, and their effects on the forest sector of different world regions and to the extent possible, individual countries.

The remainder of this paper deals with such a model, the Global Forest Products Model (GFPM). The next section presents the mathematical formulation of the static and dynamic parts of the model. This is followed by a description of the methods used to estimate the parameters and calibrate the model. We then present examples of application of the GFPM for forecasting and policy analysis. The discussion and conclusion considers the shortcomings of the model and future lines of inquiry to improve it.

GFPM structure and formulation

The GFPM calculates every year a global equilibrium across countries and products, linked dynamically to past equilibria. The static phase refers to the calculation of the equilibrium in any given year. The dynamic phase refers to the change in equilibrium conditions from year to year. More details concerning the formulation and the computer implementation are available in Buongiorno and Zhu (2014a). The current model deals with 180 countries, forest area and stock, and 14 wood products (Table 1).

Static phase: spatial global equilibrium

The spatial global economic equilibrium of the forest sector in a given year is obtained by solving the following quadratic programming problem:

$$\begin{aligned} \max Z = & \sum_i \sum_k \int_0^{D_{ik}} P_{ik}(D_{ik}) dD_{ik} - \sum_i \sum_k \int_0^{S_{ik}} P_{ik}(S_{ik}) dS_{ik} \\ & - \sum_i \sum_k \int_0^{Y_{ik}} m_{ik}(Y_{ik}) dY_{ik} - \sum_i \sum_j \sum_k c_{ijk} T_{ijk}. \end{aligned} \quad (1)$$

Table 1 Forest sector data predicted by the GFPM

Item	Production	Import	Export	Price
Forest area				
Forest stock				
CO ₂ e in forest stock				
Fuelwood	x	x	x	x
Industrial roundwood	x	x	x	x
Other industrial roundwood	x			
Sawnwood	x	x	x	x
Veneer and Plywood	x	x	x	x
Particleboard	x	x	x	x
Fibreboard	x	x	x	x
Mechanical pulp	x	x	x	x
Chemical pulp	x	x	x	x
Other fibre pulp	x	x	x	x
Waste paper	x	x	x	x
Newsprint	x	x	x	x
Printing & writing paper	x	x	x	x
Other paper & paperboard	x	x	x	x

Subject to:

$$D_{ik} = D_{ik}^* \left(\frac{P_{ik}}{P_{ik,-1}} \right)^{\delta_{ik}}, \quad (2)$$

$$S_{jk} = S_{jk}^* \left(\frac{P_{jk}}{P_{jk,-1}} \right)^{\lambda_{jk}}, \quad (3)$$

$$S_i = (S_{ir} + S_{in} + \theta_i S_{if}) \mu_i \text{ and } S_i \leq I_i, \quad (4)$$

$$\sum_j T_{ijk} + S_{ik} + Y_{ik} - D_{ik} - \sum_n a_{ikn} Y_{in} - \sum_j T_{ijk} = 0 \quad \forall i, k, \quad (5)$$

$$Y_{il} - b_{ikl} Y_{ik} = 0 \quad \forall i, k, l, \quad (5')$$

$$T_{ijk}^L \leq T_{ijk} \leq T_{ijk}^U, \quad (6)$$

$$m = m_{ik}^* \left(\frac{Y_{ik}}{Y_{ik,-1}} \right)^{s_{ik}}, \quad (7)$$

$$c_{ijk} = c_{ijk}^* \left(\frac{T_{ijk}}{T_{ijk,-1}} \right)^{\tau_{ijk}}, \quad (8)$$

$$c_{ijk} = f_{ijk} + t_{jk}^x (P_{ik,-1}) + t_{jk}^l (f_{ijk} + P_{ik,-1}), \quad (9)$$

all variables in equations (1) to (9) refer to a specific year. For each variable and parameter the subscripts i and j refer to countries and k refer to a product.

The objective function (1) defines the social surplus in the global forest sector in a given year, which competitive markets maximize (Samuelson, 1952; Takayama and Judge, 1971). This surplus is equal to the value of the products to consumers (area under all the demand curves) minus the cost of supplying the raw materials (area under their supply curves), minus the transformation cost and the transport cost between countries. The variable P is the price in constant US dollars, D the final product demand, S the raw material supply, Y the quantity manufactured, m the manufacturing cost (labour, capital, and materials excluding wood and

fibre), T the quantity transported and c the unit cost of transportation, including tariffs.

Equation (2) defines the end product demand. D^* is the current consumption at last period's price, P_{-1} is the last period's price and δ is the price elasticity. As shown in the dynamic phase below, D^* depends on last period's demand and the growth of GDP in the country.

Equation (3) defines the raw material supply (wood, other fibres, recycled paper), S^* is the current supply at last period's price and λ is the price elasticity. As shown in the section on dynamics, below, S^* depends on last period's supply, and on the change of forest stock.

Equation (4) defines drain from the forest. The subscript r refers to industrial roundwood, n to other industrial roundwood and f to fuelwood. θ is the fraction of fuelwood that comes from the forest and μ is the ratio of the drain from the forest to the harvest. I is the forest stock, which the harvest cannot exceed.

Equation (5) defines the material balance for each country and product: the quantity imported plus the domestic supply and the manufactured quantity must equal the domestic demand plus the quantity used in manufacturing other products and exports. a_{ikn} is the input of product k per unit of manufactured product n in country i . In addition, the constraint (5') allows for byproducts (secondary commodities), which result from the production of a (primary) commodity, such as sawmill residues from the production of sawnwood. b_{ikl} is the amount of byproduct l recovered per unit of manufactured commodity k .

Constraint (6) refers to the 'trade Inertia' whereby the current trade must stay within a lower bound, T^L , and upper bound, T^U , relative to the previous period (see Dynamic phase below).

Equation (7) defines manufacturing cost, m , as a function of manufactured quantity. Manufacturing is represented by activity analysis, with input-output coefficients and a manufacturing cost. The manufacturing cost is the marginal cost of the inputs not recognized explicitly by the model (labour, energy, capital, other materials). m^* is the current manufacturing cost, at last period's output, and s is the elasticity of manufacturing cost with respect to output. As shown in the next section, m^* depend on last period's manufacturing cost, and on its exogenous rate of change.

Equation (8) defines the transport cost per unit of volume for commodity k from country i to country j in any given year. c^* is the current transport cost at last period's trade, and τ is the elasticity of transport cost with respect to trade. As shown in the next section, c^* depends on last period's transport cost, and on the exogenous changes of freight rates and taxes. The transport cost in the base year is defined by equation (9) where f is the freight cost, and t^x and t^l are the export and import ad-valorem tax rates, respectively.

Upon solution of the programming problem defined by equations (1) to (9), the shadow prices of the material balance constraints (5) give the market-clearing prices for each commodity and country.

Dynamic phase

The dynamic phase of the GFPM describes the changes in the condition of the global equilibrium from one period to the next. The equations governing the inter-equilibrium periodic changes are listed below. (Unless otherwise indicated, variables refer to one

country, one commodity and one year. Rates of change refer to a multi-year period.)

$$r_p = (1 + r_a)^p - 1, \quad (10)$$

$$\Delta v_p = p \Delta v_a, \quad (11)$$

$$D^* = D_{-1}(1 + \alpha_y g_y + \alpha_{D-1} g_{D-1} + \alpha_0), \quad (12)$$

$$S^* = S_{-1}(1 + \beta_I g_I), \quad (13)$$

$$S^* = S_{-1}(1 + \beta_y g_y), \quad (14)$$

$$A = (1 + g_a)A_{-1}, \quad (15)$$

$$g_{aa} = (\alpha_0 + \alpha_1 y') e^{\alpha_2 y'}, \quad (16)$$

$$y' = (1 + g_y') y'_{-1}, \quad (17)$$

$$I = I_{-1} + G_{-1} - p S_{-1} \quad (18)$$

$$g_{ua} = \gamma_0 \left(\frac{I_{-1}}{A_{-1}} \right)^\sigma, \quad (19)$$

$$g_I = \frac{I - I_{-1}}{I_{-1}}, \quad (20)$$

$$a = a_{-1} + \Delta a, \quad (21)$$

$$m^* = m_{-1}(1 + g_m), \quad (22)$$

$$c^* = c_{-1} + \Delta f + t^x P_{-1} - t_{-1}^x P_{-2} + t^I (f + P_{-1}) - t_{-1}^I (f_{-1} + P_{-2}), \quad (23)$$

$$f = f_{-1} + \Delta f, \quad t = t_{-1} + \Delta t, \quad (23')$$

$$T^L = T_{-1}(1 - \epsilon)^p, \quad T^U = T_{-1}(1 + \epsilon)^p. \quad (24)$$

Equation (10) defines the periodic exponential rate of change, r_p , as a function of the annual exponential rate of change, r_a , and the length of a period in years, p ; and equation (11) defines the periodic linear rate of change, Δv_p as a function of the annual linear rate of change, Δv_a .

Equation (12) defines the periodic demand shifts, where g_y is the GDP periodic growth rate, α_y is the elasticity of demand with respect to GDP, α_{D-1} is the elasticity of demand with lagged demand, g_{D-1} is the lagged periodic consumption growth rate and α_0 is the periodic trend. Equation (12) together with equation (2) implies adaptive expectations or imperfect foresight. Demand is a function of the expected, permanent, trend of price and GDP. α_{D-1} being a positive fraction implies that expectations adjust each period by a proportion of the difference between the last observation and the expectation for that period (Johnston, 1984, p. 348).

Equation (13) define the shifts of roundwood supply, where g_I is the periodic rate of change of forest stock (endogenous, see below) and β is the elasticity. There is one equation of this type for industrial roundwood (logs and pulpwood), fuelwood, and other industrial roundwood. Equation (14) defines the supply shifts of waste paper and other fibre pulp.

Equation (15) expresses the changes in national forest area, where A is the forest area and g_a is the periodic rate of forest area change. The annual rate of forest area change, g_{aa} , is defined by equation (16) where y' is the income per capita, predicted from equation (17). For each country, α_0 is calibrated automatically so

that in the base year the observed g_{aa} is equal to the g_{aa} predicted by (16) given the income per capita y' .

The national forest stock evolves over time according to the growth-drain equation (18) where I is the forest stock at the beginning of the current period, $G_{-1} = (g_a + g_u + g_u^*)I_{-1}$ is the change of forest stock without harvest during the previous period, g_u is the periodic rate of forest growth on a given area without harvest and g_u^* is the adjustment of periodic rate of forest growth on a given area without harvest. The last is exogenous, for example, to represent the effect of invasive species, or of climate change. (The forest stock I is: $I_t = U_t A_t$, where A_t is the area and U_t is the stock per unit area (stock density). Without harvest, the stock annual ($p = 1$) growth rate is $dI/I = dU/U + dA/A$ or $g_1 = g_u + g_a$. Thus, the level of stock, without harvest, changes according to $I_t = I_{t-1}(1 + g_1) = I_{t-1}(1 + g_u + g_a)$. With a harvest S_{t-1} from $t - 1$ to t this becomes $I_t = I_{t-1}(1 + g_u + g_a) - S_{t-1}$. With the above notations $I_{t-1}(g_u + g_a) = G_{t-1}$, the change in forest stock without harvest, which leads to equation (18) except for the additional exogenous change g_u^* .) The periodic rate of forest growth, g_u , is based on the annual rate of forest growth, g_{ua} , defined by equation (19) where σ is negative, so that g_{ua} decreases with stock per unit area. For each country the GFPM calibrates γ_0 automatically so that in the base year the observed g_{ua} is equal to the g_{ua} predicted by (19) given the stock per unit area, I/A . Equation (20) then gives the periodic rate of change of forest stock net of harvest, which is used in equation (13) to shift the wood supply curve.

Equation (21) expresses the changes in the input-output coefficients a in equation (5), for example to reflect the increasing use of recycled paper in paper manufacturing. Δa is the periodic change in input-output coefficient. The manufacturing cost function shifts exogenously over time at the annual periodic exponential rate g_m as in equation (22). The transport cost function (8) shifts exogenously over time according to equations (23) and (23'), a recursion of equation (9) where Δf and Δt are periodic changes in freight cost and tax rates, respectively. Last, equation (24) defines the periodic changes in trade inertia bounds, where ϵ is the absolute value of the maximum annual rate of change in trade flow (exogenous).

Timber supply with carbon markets

In the eventual presence of active carbon markets, wood producers receive a payment for leaving wood in the forest to sequester carbon. Then, the marginal cost of wood is the marginal cost of harvesting and local delivery represented by equation (3), plus the opportunity cost per m^3 of losing the carbon offset payment by not leaving the wood in the forest. Like demand, and manufacturing and transport cost, the wood supply is approximated by the tangent at the current equilibrium point (P_0, S_0):

$$P = a + bS, \quad (25)$$

where $b = P_0/\sigma S_0$, $a = P_0 - bS_0$. In the presence of carbon offset payments, this wood supply equation becomes

$$P = a + bS + \omega(P^c - P_{-1}^c). \quad (26)$$

where ω is the CO₂e content of the forest stock ($t \text{ m}^{-3}$), P^c is the current price of CO₂e ($\$ \text{ t}^{-1}$) and P_{-1}^c is the price of CO₂e in the previous period.

Allowable cut constraints

In addition to the permanent constraints stating that in any given year the total wood drain from the forest of a country cannot exceed the stock equation (4), optional allowable cut constraints specify that the drain must be less than a specified fraction of the current annual gross growth of the forest stock, i.e. the amount by which the forest stock would grow if there were no harvest.

The general form of the constraint is:

$$S \leq \max\left(\frac{aG}{p, 0}\right). \quad (27)$$

where S is the total wood drain from the forest defined by equation (4), G is the periodic change of growing stock without harvest equation (18), and a is the maximum ratio of inventory drain to the growth of growing stock.

Model calibration and validation

Estimation of the I-O coefficients and manufacturing costs

The I-O coefficients, a_{ikn} , and manufacturing costs, m_{ik} , of the GFPM are determined simultaneously by a calibration procedure based on FAOSTAT data. Each I-O coefficient in a year and country is the ratio of the amount of input used in manufacturing a product to the amount of output. However, no systematic international data exist on how much, say, mechanical or chemical pulp is used in a country to make newsprint, and although there are data on the total production of each product they are imprecise. The GFPM calibration procedure estimates the amount of input going into an output while adjusting the production of the input or output if needed based on prior knowledge of manufacturing processes. This then provides an estimate of the I-O coefficients, which together with data on local prices give an estimate of the manufacturing costs.

The estimates of total production and input-output quantities for a particular country and year are obtained by goal programming, conditional on the production and trade data and on prior bounds on the I-O coefficients and manufacturing cost. The method adjusts the production data if they are inconsistent with prior knowledge on the possible range of the input-output coefficients. It minimizes the sum of the weighted absolute deviations between estimated production and reported production, and of the sum of the weighted absolute difference between the estimated input and the input implied by prior I-O coefficients suggested by technical knowledge.

In the following formulation, all the variables and data refer to a specific country and year, the subscripts k and n refer to products. Variables are in capital letters and data are in lower cases. All the variables are non-negative.

$$\min \beta \sum_{k \in A} w_k (Y_k^+ + Y_k^-) + (1 - \beta) \sum_{k \in I} \sum_{n \in O} (w_k w_n)^{1/2} (Y_{kn}^+ + Y_{kn}^-). \quad (28)$$

Subject to:

$$Y_k + Y_k^- - Y_k^+ = q_k \quad \forall k \in A, \quad (29)$$

$$Y_{kn} - \bar{a}_{kn} Y_n + Y_{kn}^- - Y_{kn}^+ = 0 \quad \forall k \in I, n \in O, \quad (30)$$

$$Y_k \geq x_k - z_k \quad \forall k \in F, \quad (31)$$

$$Y_k - \sum_{n \in O} Y_{kn} = x_k - z_k \quad \forall k \in R, \quad (31')$$

$$Y_{kn} - a_{kn}^U Y_n \leq 0 \quad \forall k \in I, n \in O, \quad (32)$$

$$Y_{kn} - a_{kn}^L Y_n \geq 0 \quad \forall k \in I, n \in O, \quad (32')$$

$$\sum_{k \in I} Y_{kn} - a_n^U Y_n \leq 0 \quad \forall n \in O, \quad (33)$$

$$\sum_{k \in I} Y_{kn} - a_n^L Y_n \geq 0 \quad \forall n \in O, \quad (33')$$

$$Y_k - \sum_{n \in F} r_{kn}^U Y_n \leq \sum_{n \in F} (z_n - x_n) r_{kn}^U \quad \forall k \in E, \quad (34)$$

$$Y_k - \sum_{n \in F} r_{kn}^L Y_n \geq \sum_{n \in F} (z_n - x_n) r_{kn}^L \quad \forall k \in E, \quad (34')$$

$$p_k Y_k - \sum_{n \in I} Y_{nk} p_n \leq m_k^U \quad \forall k \in O, \quad (35)$$

$$p_k Y_k - \sum_{n \in I} Y_{nk} p_n \geq m_k^L \quad \forall k \in O. \quad (35')$$

In the objective function (28) the variables Y_k^+ , Y_k^- are the deviations of estimated production of product k above or below the production reported in FAOSTAT, and Y_{kn}^+ , Y_{kn}^- are the deviations of estimated input of product k in product n above or below the input implied by prior input-output coefficients. In current applications (Buongiorno and Zhu, 2014b), the weights w_k and w_n are commensurate with the product prices to allow more deviation between observed and estimated production for cheap products, and $\beta = 0.90$ to give more weight to the deviations between observed and actual production than to deviations between estimated and expected input, because data (possibly imprecise) are available for Y_k and Y_n but no direct data exist for Y_{kn} .

The constraints (29) define the deviations of the estimated production Y_k from the reported production in FAOSTAT, q_k . A is the set of products. In constraints (30), Y_{kn}^+ , Y_{kn}^- are the deviations of the estimated input of product k in product n , Y_{kn} , above or below the input expected from the prior input-output coefficients. The parameter $\bar{a}_{kn} = (a_{kn}^L + a_{kn}^U)/2$ is the expected input k per unit of output n , and a_{kn}^L , a_{kn}^U are the lower and upper bound on input k per unit of output n . I is the set of inputs, O is the set of outputs.

The constraints (31) specify that the apparent consumption of the end products must be non-negative (exact equality must hold as in (31') for raw materials or intermediate products used in making other products). The reported imports and exports, z_k and x_k , are assumed to be error free, as they usually go through customs and thus are usually more reliable than production data. F is the set of end products, and R is the set of raw materials or intermediate products.

The constraints (32) and (32') keep the estimated input-output coefficients, such as the amount of industrial roundwood per unit of sawnwood, between prior lower and upper bounds a_{kn}^L , a_{kn}^U

suggested by engineering knowledge. In addition, the constraints (33) and (33') express the fact that for paper and paperboard the total amount of the different fibres (mechanical pulp, chemical pulp, other fibre pulp, waste paper) used in manufacturing a ton of product, must also lie between prior technical limits, a_n^l , a_n^u , the lower and upper amount of total fibre used per unit of product n .

The constraints (34) and (34') express the feasible post-consumer recovery, where r_{kn}^u is the upper bound on the recovery rate of product k (say waste paper) from product n (say newsprint), and r_{kn}^l is the lower bound. E is the set of recycled products. The last constraints (35) and (35') refer to the upper and lower bounds on the unit manufacturing cost, where the prices, p_k , and p_n are the world prices (unit values of world exports) for net exporters, and the world prices plus the transport costs and tariffs for net importers.

After solving the problem specified by equations (28) to (35'), the estimated input-output coefficients, \hat{a}_{kn} , the amounts of product k used in making product n , are given by:

$$\hat{a}_{kn} = \frac{Y_{kn}}{Y_n} \forall k \in I, n \in O. \quad (36)$$

The attendant manufacturing costs are estimated by assuming a market equilibrium with no pure profits so that the manufacturing cost (for labour, materials excluding wood and fibre and a normal return to capital) is equal to the price of the output minus the cost of wood and fibre input, that is:

$$\hat{m}_k = p_k - \sum_{n \in I} \hat{a}_{nk} p_n \forall k \in O. \quad (37)$$

The strong assumption underlying this definition of manufacturing cost was predicated by the paucity of international data on manufacturing costs in forest industries.

Any deviation of the estimated value of production from the reported value in the FAOSTAT database is revealed by a positive value of the deviational variables, Y_k^+ for an overestimation, or Y_k^- for an underestimation. An example of calibration results is in Table 2, for China in 2011. In that year, it took approximately 1.05 m³ of industrial roundwood (commodity 81) to produce 1 m³ of sawnwood (commodity 83). The corresponding manufacturing cost of sawnwood (labour, capital, energy and other materials excluding industrial roundwood) was about \$158 m⁻³. The

table shows the heavy use of waste paper (commodity 90) in China in the manufacture of all three grades of paper and paperboard (commodities 91, 92 and 93). The estimated production was the same as that reported in FAOSTAT, except for industrial roundwood for which the estimated production exceeded the reported production by 8.4 million m³ or 7.9 percent in 2011.

With input-output coefficients and manufacturing costs determined in this way for all other countries, and the end-product demand and wood supply equations positioned with the price and quantity in each country, the solution of the global equilibrium expressed by equations (1) to (9) closely replicates the input data, in terms of production, consumption, net trade and prices in all countries and for all products.

Other parameters

Demand is perhaps the most important determinant of future developments of the forest sector. The general functional form used in estimating the demand parameters of equations (2 and 12) was:

$$\ln C_{it} = \delta \ln P_{it} + \alpha Y_{it} + \alpha_{D-1} C_{it-1} + \sum_i d_i + \varepsilon_{it}, \quad (38)$$

where the subscript i refers to a country and t to a year. C is apparent national consumption (production + imports - exports) of a particular product. P is the real unit price in \$US of 2011, measured by the unit value of imports for net importing countries and by the unit value of exports for net exporting countries. Y is the gross domestic product in constant \$US of 2011. C_{t-1} is consumption in the previous year. d is a dummy variable to account for other variables that may affect consumption in a particular country, such as construction techniques for solid wood products or literacy rates for paper products.

The parameters of equation (38) were estimated with panel annual data from 1992 to 2012, with a varying number of countries due to missing data, and with the fixed-effects statistical procedure (Wooldridge, 2004, p. 267). The resulting elasticities with respect to GDP, price and lagged consumption are given in Table 3. For fuelwood and other industrial roundwood (wood used in the round such as poles, pilings and posts), the GDP elasticity was estimated while constraining the price elasticity to -0.10.

Table 2 Input-output coefficients and manufacturing costs calibrated for China in 2011

Input	Output								
	83 m ³ m ⁻³	84 m ³ m ⁻³	85 m ³ m ⁻³	86 m ³ m ⁻³	87 m ³ t ⁻¹	88 m ³ t ⁻¹	91 t t ⁻¹	92 t t ⁻¹	93 t t ⁻¹
81	1.05	1.05	0.95	0.95	1.30	1.30			
87							0.00	0.00	0.012
88							0.00	0.00	0.283
89							0.00	0.00	0.164
90							1.10	1.10	0.576
Manufacturing cost	\$ m ⁻³ 157.6	\$ m ⁻³ 445.7	\$ m ⁻³ 198.4	\$ m ⁻³ 317.9	\$ t ⁻¹ 397.3	\$ t ⁻¹ 535.8	\$ t ⁻¹ 441.9	\$ t ⁻¹ 733.3	\$ t ⁻¹ 520.2

Commodity codes: 81 Industrial roundwood, 83 sawnwood, 84 veneer and plywood, 85 particleboard, 86 fibreboard, 87 mechanical pulp, 88 chemical pulp, 89 other fibre pulp, 90 waste paper, 91 newsprint, 92 printing & writing paper, 93 other paper and paperboard.

Table 3 Elasticities of demand for end products used in the GFPM

	$\ln Y$	$\ln P$	$\ln C_{-1}$
Fuelwood	0.10 (0.03) ^a	-0.10 ^b	0.78 (0.03)
Other industrial roundwood	-0.05 (0.02)	-0.10 ^b	0.78 (0.02)
Sawnwood	0.14 (0.02)	-0.10	0.56 (0.02)
Veneer and plywood	0.24 (0.02)	-0.20	0.56 (0.02)
Particleboard	0.22 (0.03)	-0.28	0.60 (0.02)
Fibreboard	0.55 (0.04)	-0.26	0.54 (0.02)
Newsprint	0.11 (0.02)	-0.17	0.53 (0.02)
Printing and writing paper	0.31 (0.02)	-0.26	0.52 (0.02)
Other paper and paperboard	0.23 (0.02)	-0.09	0.60 (0.02)

^aNumbers in parentheses are standard errors.

^bConstrained price elasticity.

Forest area changes are represented in the GFPM by an environmental Kuznets curve linking the rate of forest area change to income per capita (Koop and Tole, 1999). Equation (16) was estimated with data from FAO (2010), leading to $\alpha_1 = 0.0014$ (standard error = 0.0005) and $\alpha_2 = -0.0898$ (standard error = 0.0327). The constant α_0 was calibrated for each country so that the initial growth rate in 2011 was equal to the growth rate predicted with the equation. The top panel of Figure 1 shows the evolution of the annual rate of change of forest area with GDP per capita on average, and for selected countries. For example, for Brazil, the initial negative growth rate of -0.5 per cent per year increases to reach 0 at an income per capita near \$20,000 year⁻¹, becomes highest at about \$30,000 capita⁻¹ and then declines progressively. The high initial growth rate of China decreases monotonically, while the low initial growth rate of Australia increases monotonically. At high income per capita the growth rate of all countries converges to zero, and the forest area stabilizes.

The growth rate of forest stock in the absence of harvest, an inverse function of the density of forest stock described by equation (19), was also estimated with data from FAO (2010), leading to $\sigma = -0.45$ (standard error = 0.12). The constant γ_0 was recalibrated for each country so that the predicted value for 2011 was equal to the observed value. The lower panel of Figure 1 shows the average relation between the growth rate of forest stock and the forest density, and the relations for Australia, Brazil and China.

The supply elasticities for fuelwood and industrial roundwood with respect to price and growing stock were taken from Turner et al. (2006). The freight cost between countries was estimated as the difference between unit value of imports and exports. Data on import tariff duties came from the World Trade Organization database (WTO, 2013). The trade inertia parameters were based on observations on the past variation of imports and exports. For lack of data, some of the parameters had to be set intuitively, based mostly on the dynamic behavior of the model, for

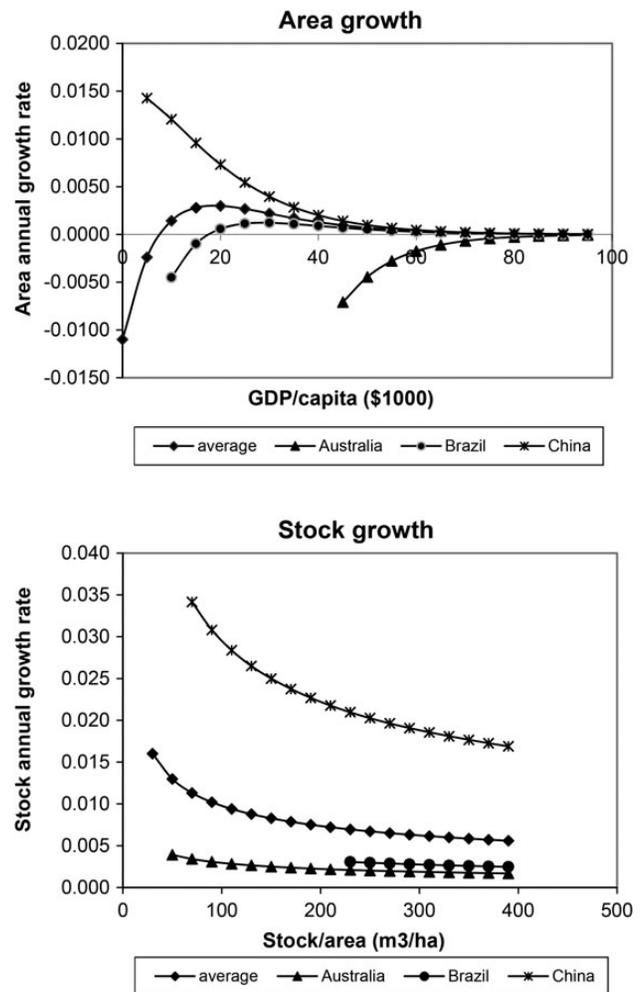


Figure 1 Growth rates (percent/100) of forest area and forest stock implied by the GFPM equations, for three countries, and on average across countries.

example the proportion of fuelwood that came from the forest in each country, to supplement the data available in the Global Resources Assessment (FAO, 2010).

Computer software

After local linear approximation of the demand, supply and cost functions (2), (3) and (7), the objective function (1) is quadratic in D , S , Y and T . Thus, the equilibrium in a given year is obtained by solving a quadratic optimization problem with linear constraints. The solution is computed with an interior point solver (BMPD, Mészáros, 1999). The GFPM input and output for calibration and simulation is facilitated by Excel spreadsheets and graphics. A recent version of the complete software, its documentation and a pre-calibrated dataset are available freely for academic research (Buongiorno and Zhu, 2014a,b).

Applications

Models such as the GFPM are useful for forecasting and policy analysis. Forecasting consists in attempting to predict the future

condition of the forest sector conditional on specific assumptions regarding future macroeconomic conditions, especially income and demographic growth. Policy analysis involves comparing model forecasts with different assumptions regarding future policies such as increased demand for energy wood (Raunika and Buongiorno, 2010) or offset payments to encourage carbon sequestration in forests (Buongiorno and Zhu, 2013).

Forecasting

Figures 2-4 show selected predictions of production and prices obtained with the GFPM. The base year was 2011 and the predictions were carried up to 2065, conditional on the demographic and economic growth predictions of the Intergovernmental Panel on Climate Change (IPCC). The specific scenario was B2, the

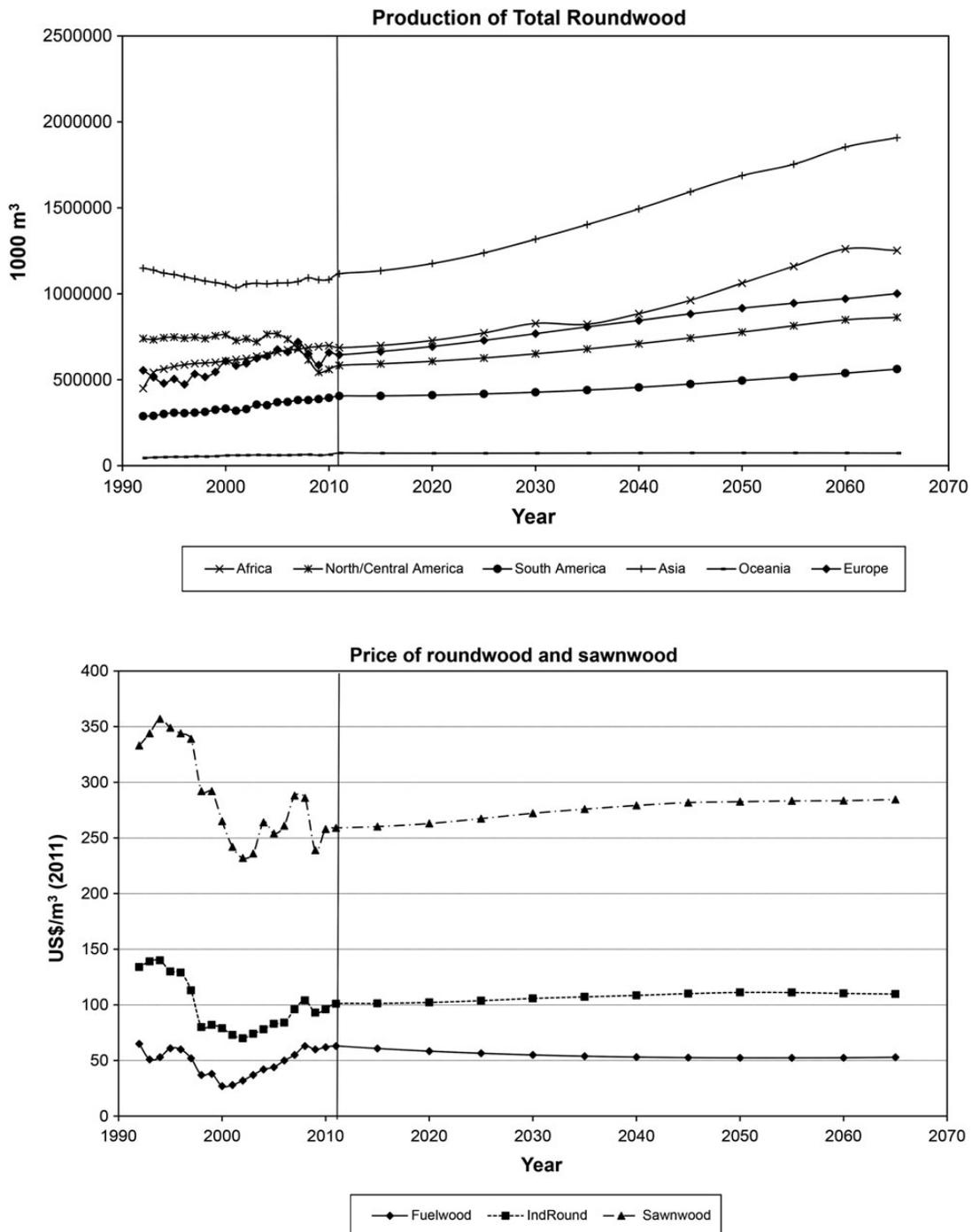


Figure 2 Predicted production and price of total roundwood.

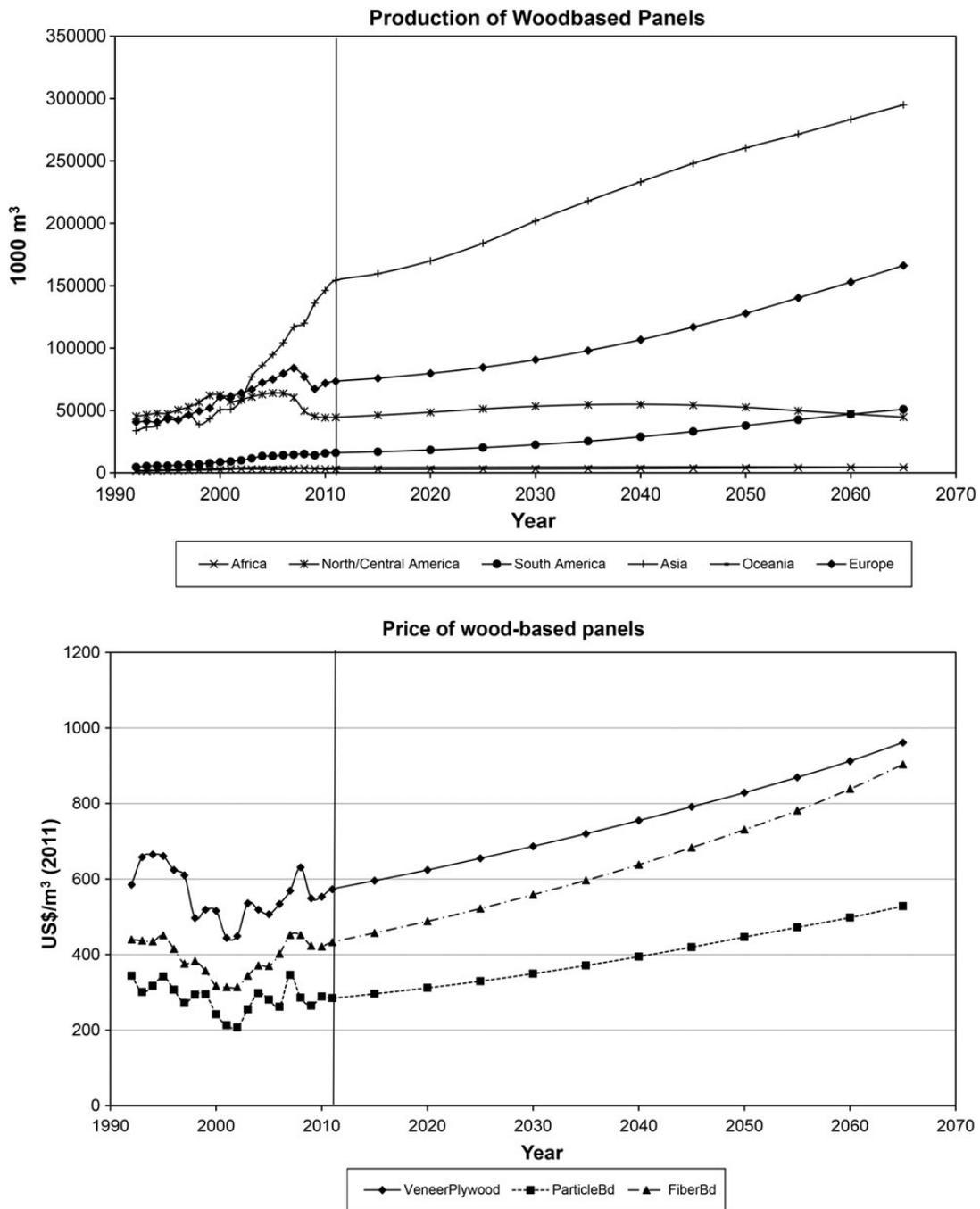


Figure 3 Predicted production and price of wood-based panels.

intermediate scenarios among the three adapted by the USDA Forest Service for the last Resources Planning Act (RPA) Assessment (USDA Forest Service, 2012a).

With this scenario, according to the GFPM projections in the upper panel of Figure 2, the world total annual roundwood production (fuelwood + industrial roundwood) would increase by 2.1 billion m³ (61 per cent) from 2011 to 2065. The largest increase was in Asia (792 million m³ or 71 per cent increase),

followed by Africa (565 million m³ or 82 per cent) and Europe, including Russia (355 million m³ or 55 per cent). Meanwhile, there was only modest changes in the real-world price of roundwood and sawnwood (Figure 2, lower panel). (World prices are measured by the unit value of world exports, with the value of exports expressed in constant \$US of 2001.) The prices of industrial roundwood and sawnwood would rise almost in parallel, by 9 and 10 per cent, respectively, while

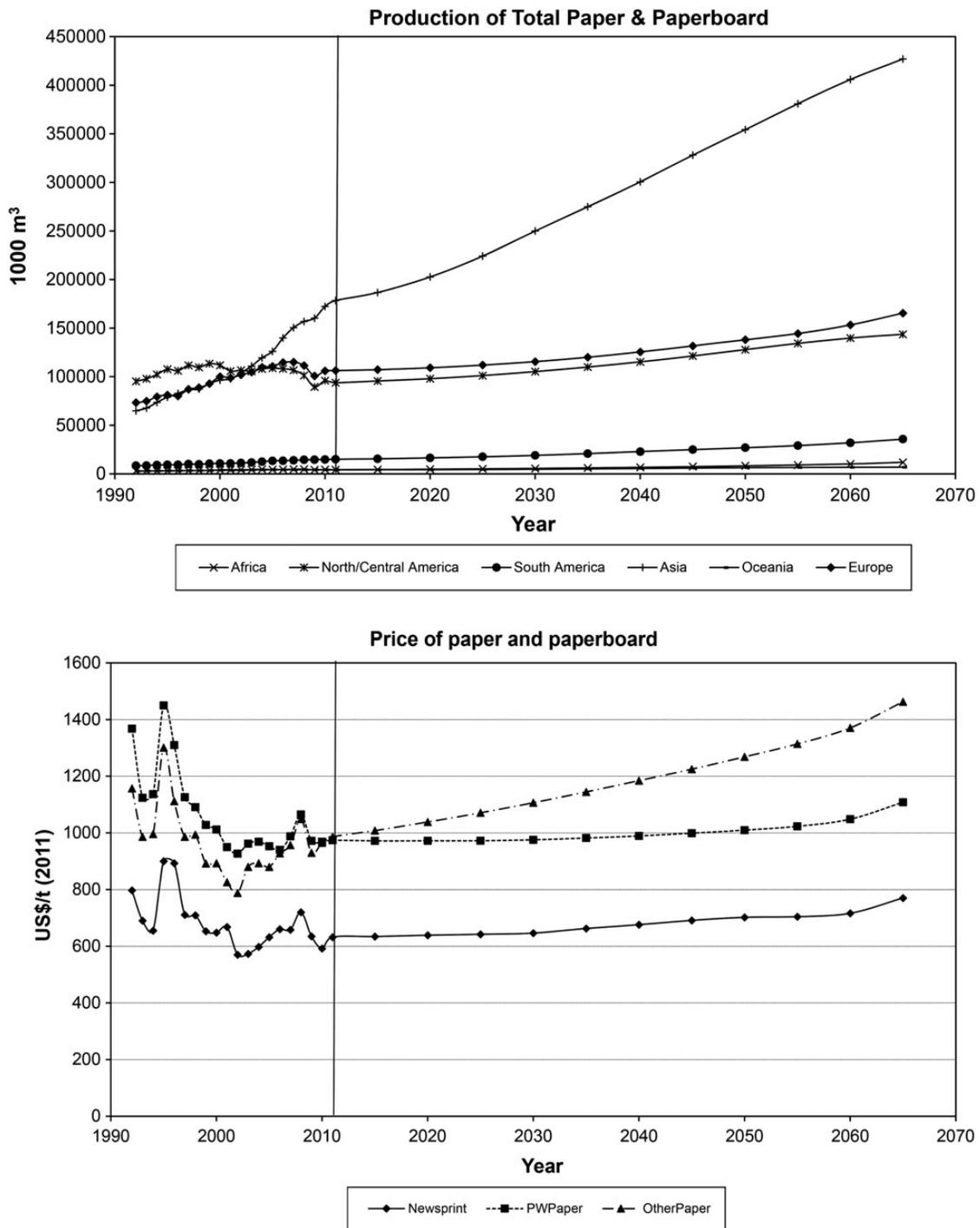


Figure 4 Predicted production and price of paper and paperboard.

the price of fuelwood would decrease by 16 per cent, to about \$50 m⁻³ in 2065.

The world annual production of wood-based panels (veneer and plywood, particleboard, and fibreboard) was projected to increase by 270 million m³ (91 per cent) from 2011 to 2065. The main increase was in Asia (141 million m³), followed by Europe (93 million m³) and

South America (35 million m³). In contrast, there was practically no change in production from North/Central America (Figure 3, top panel). Over the 54 years considered, the price of wood-based panels increased markedly (Figure 3, lower panel), by 109 per cent for fibreboard, 85 per cent for particleboard, and 68 per cent for veneer and plywood.

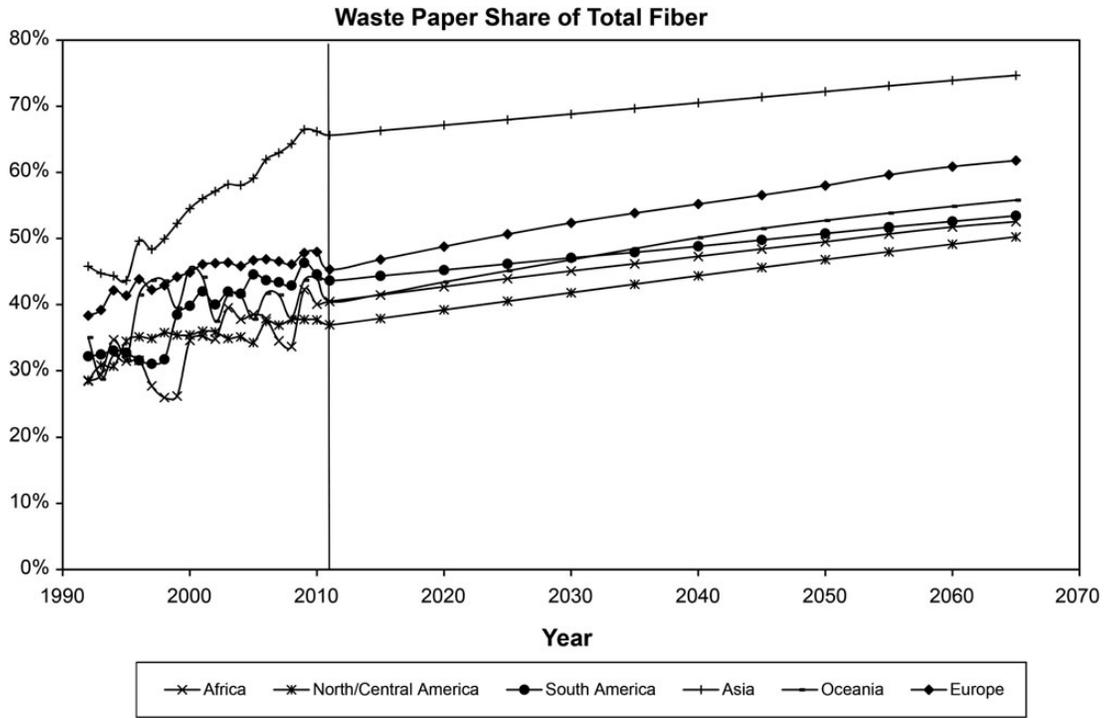


Figure 5 Predicted share of waste paper in total fibre used in making paper and paperboard.

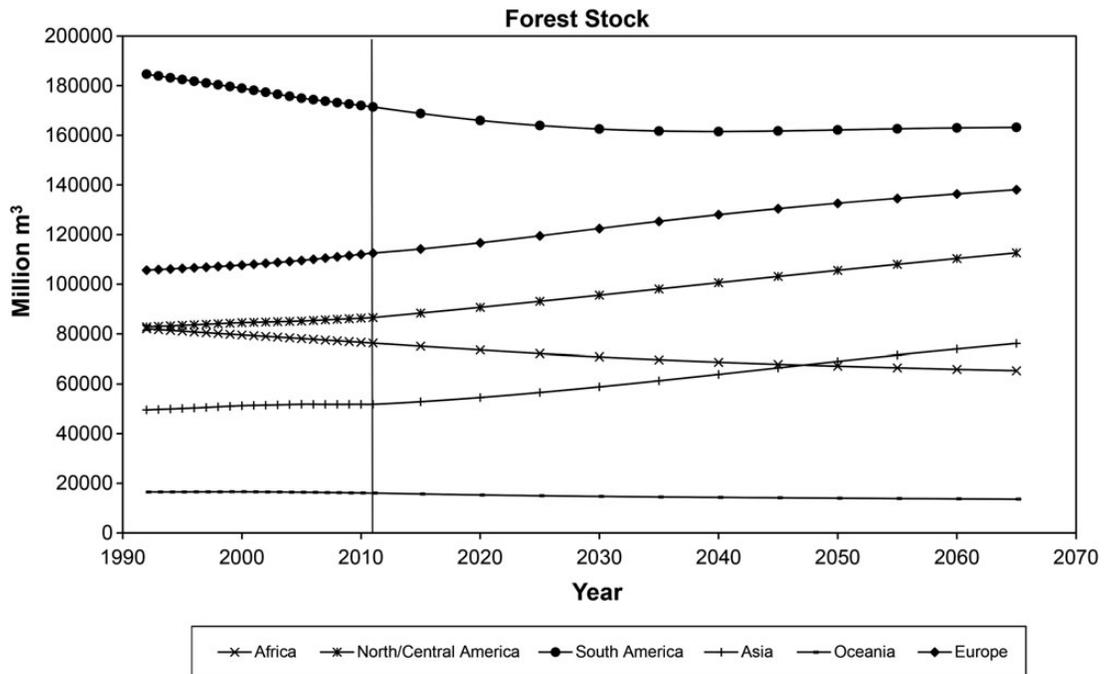


Figure 6 Predicted growing stock.

Figure 4 shows the predictions of production and prices of paper and paperboard. The world annual paper and paperboard production increased by 389 million t (97 per cent) over the 54 years'

projection. The largest increase (249 million t, or 139 per cent) was in Asia, while production increased more modestly in Europe (59 million t or 56 per cent), North/Central America (50 million t

or 53 per cent) and South America (21 million t or 138 per cent). The world price of newsprint and printing and writing paper was projected to increase by 22 and 14 per cent, respectively from 2011 to 2065, and the price of other paper and paperboard increased most rapidly, by 48 per cent over the same period.

The projected growth of paper and paperboard production from 2011 to 2065 was facilitated by the increasing utilization of recycled waste paper instead of wood pulp. Figure 5 shows that the share of waste paper in total fibre utilization went from 66 per cent in Asia to 75 per cent from 2011 to 2065. In Europe, it increased from 45 to 62 per cent and in North/Central America from 37 to 50 per cent. In conjunction with this increase of waste paper utilization, the world price of waste paper increased by 95 per cent from \$187 t⁻¹ in 2011 to \$364 t⁻¹ in 2065.

Another example of GFPM prediction with this scenario is in Figure 6, showing the expected future growing stock by world region. From 2011 to 2065 the world growing stock increased by 54 billion (1000 million) m³, or 11 per cent, of which 26 billion m³ (23 per cent) in Europe and 26 million m³ (30 per cent) in North America. Meanwhile, the growing stock decreased by 11 million m³ (14 per cent) in Africa, 8 billion m³ (5 per cent) in Asia and 2 billion m³ (15 per cent) in Oceania. The forest area, not shown here, followed a similar pattern of increase in Europe and North America, and decline in Africa, Asia and Oceania.

Policy analysis

An example of application of the GFPM in policy analysis deals with the consequences of offering offset payments to forest owners for carbon, or equivalent carbon dioxide (CO₂e) stored in trees (Buongiorno and Zhu, 2013). The effect of offset payments for carbon sequestration is to increase the marginal cost of harvesting wood by an amount equal to the offset payment per unit of harvest volume that could be earned by not harvesting, the variable P^c in equation (26). The study simulates the effect of offset payments from \$15 to \$50 t⁻¹ of CO₂e. In one simulation the offset payments occur in all countries, while in another a more limited policy concentrates payments in developed countries only.

Table 4 shows the changes in stock of CO₂e obtained in 2030 with payments of \$30 t⁻¹ CO₂e that start in 2015. The global policy increases carbon storage by about 9 billion (1000 million) t of CO₂e, or 6 per cent. But, when the policy is applied in developed countries only so that carbon sequestration increases in developed countries, it decreases by 3.4 billion t in developing countries, leading to only 3 per cent increase in global carbon storage.

This 'leakage' resulting from a unilateral rather than global application of the policy is due to the difference in wood harvest induced by payments for carbon sequestration. Table 5 shows for example that a payment of \$30 t⁻¹ of CO₂e decreases the world production of roundwood (fuelwood and industrial roundwood) in 2030 by 9 per cent with a global policy, but by only 4 per cent when the policy applies to developed countries only. This is due to the increase in harvest under the partial policy in South America and Asia in particular, which more than exceeds the decrease in Europe and North America.

The changes in the revenues of wood producers, measured by the value of fuelwood and industrial roundwood production at prevailing real prices, are in the second and third columns of Table 6. When offset payments of \$30 t⁻¹ of CO₂e were applied in all countries world timber revenues increased by 54 per cent relative to the

Table 4 Change of CO₂e stored in living forest biomass from 2015 to 2030 due to offset payments of \$30 t⁻¹ CO₂e applied globally or in developed countries only

	Offset payment applied	
	All countries (million t)	Developed countries only (million t)
The US	928	1563
Chile	243	-365
China	305	-859
Indonesia	292	-324
France	231	392
Germany	115	317
Russian Federation	919	1308
Sweden	519	718
Developed	5095	8455
Developing	4021	-3433
World	9116	5022

Source: Buongiorno and Zhu (2013).

Table 5 Change of annual total roundwood production in 2030 due to offset payments of \$30/t CO₂e applied globally or in developed countries only from 2015 to 2030

	Offset payment in:	
	All countries (million m ³)	Developed countries only (million m ³)
Africa	-40	-1
North/Central America	-48	-77
South America	-46	44
Asia	-75	55
Oceania	-8	-11
Europe	-91	-148
Developed	-139	-248
Developing	-169	110
World	-308	-138

Source: Buongiorno and Zhu (2013).

base scenario because the increases in prices of fuelwood and industrial roundwood largely exceeded decreases in production. Two-thirds of the timber revenue increase occurred in developing countries. With offset payments of \$30 t⁻¹ of CO₂e in developed countries only, the world timber revenues still increased by 51, and 87 per cent of the increase was in developing countries.

In addition to increased timber revenues, producers also benefit from direct offset payments for carbon storage in forests. The last two columns in Table 6 show the average yearly offset payments received by producers in 2030 at \$30 t⁻¹ of CO₂e. The global offset payment (i.e. the cost of the policy) was nearly the same when applied to all countries or to developed countries only, 17–18 per cent of the change in global timber revenue. However, with payments to all countries, nearly 700 million t per year of

Table 6 Change in timber harvest revenues and offset payments in year 2030 with offset payments of \$30/t CO₂e applied globally or in developed countries only from 2015 to 2030

Region	Change in timber harvest revenues with:		Offset payments with:	
	Offset payments in all countries (million \$)	Offset payments in developed countries only (million \$)	Offset payments in all countries (million \$)	Offset payments in developed countries only (million \$)
Africa	25 304	27 004	2424	142
North/Central America	20 071	10 839	3864	6416
South America	12 629	20 015	2543	0
Asia	42 141	50 380	3811	0
Oceania	2114	1034	619	900
Europe	20 453	7436	7730	12 377
Developed	40 789	15 278	12 031	20 783
Developing	81 923	101 430	8960	0
World	122 712	116 708	20 992	20 783

Source: [Buongiorno and Zhu \(2013\)](#).

CO₂e were stored globally in 2030, of which 400 million t in developed countries and 300 million t in developing countries. With payments limited to developed countries, only 400 million t per year of CO₂e were stored globally in 2030, with an addition of 700 million t per year in developed countries countered by a reduction of 300 million t per year in developing countries.

Discussion and conclusion

The search for global forest sector models is motivated by the increasingly connected world economy. In that context, timber production and prices in a country, and all the attendant activities that depend on them, are largely determined by global competitive forces and by global policies. This has been recognized, for example, in the forest portion of the 2010 Resources Planning Act report ([USDA Forest Service, 2012b](#)) which anchors the US' assessment in an international context.

The particular model described above, the GFPM, attempts to maximize the global-national connection, and thus its relevance for national forecasting or policy analysis, by building from the ground up. The basic data are for individual countries. The requirement of getting projections for each of 180 countries was requested by the specifications of the first GFPM version ([FAO, 1997](#)). Although dealing with so many countries seems daunting, it has notable advantages: the need of a general methodology that can apply to very different countries, the connection to the basic national data on forest resources and forest industries ([FAO, 2010, 2014](#)) and the facilitation of knowledgeable reviews and comments. Indeed, although few experts can comment on data and projections for vast regions like Asia or South America, more are likely to know the situation and prospects for specific countries such as India or Brazil.

The close connection between the GFPM database and the FAO statistics allows for a yearly updating of the GFPM parameters as soon as the FAOSTAT data are published. However, as observed above, the GFPM approach does not accept all official statistics at face value. Its calibration procedure may modify production statistics if they are not consistent with prior knowledge concerning

input-output relations in the transformation of wood into fibre and solid products. Thus, the method combines 'hard data' such as those in the FAOSTAT with 'soft data' on technical processes, along the lines suggested by [Forrester \(1980\)](#). As indicated above, other such soft data must also be used where no alternative source is available, such as the proportion of fuelwood that comes from forests, or some elasticities of demand and supply.

The role of a model is to 'bring the real world to the laboratory' ([Holling et al., 1986](#)), where it is used for various experiments. Examples of such experiments with the GFPM include forecasting the future state of the sector, or investigating its response to various policy changes such as trade agreements, increased bioenergy utilization or carbon offset payments in forests. In terms of forecasting, the results presented above suggest that wood supply should be adequate to satisfy the projected demand in the next 50 years, in the sense that the real price of wood is not expected to increase, and the global forest stock would increase, although it would continue to decline in Africa and South America. Regarding policy of offset payments for carbon sequestration, the results show the importance of a global policy, applied equally to rich and poor countries. Otherwise, unilateral policies concentrating on rich countries lead to 'leakage' and inefficiencies due to the reaction of poor countries.

It should be kept in mind that these and other results are obtained with a model that simulates reality only approximately. Although the GFPM is calibrated so that the base year solution is, by construction, very close to the observations, it has been observed that the model replicates only the general trends of historical data series and that the errors increase with the level of disaggregation ([Buongiorno et al., 2003](#), pp. 75–88). Considerable work remains to be done to improve the dynamic calibration of the model, possibly with better estimates of some of the parameters, data permitting. In the meantime, sensitivity analysis can be used to judge how some changes in assumptions affect the projections. Other models than the GFPM are also available, such as the EFI-GTM ([Kallio et al., 2004](#)), the FASOM ([Adams et al., 1996](#)), the GLOBIOM ([Lauri et al., 2013](#)), with which alternative projections can be obtained to assess the range of possible outcomes.

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