6 Global Forest Products Trade Model

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Abstract

This chapter introduces the Global Forest Products Model (GFPM). The general model structure and the mathematical formulation of the GFPM are provided and key differences and similarities to the modeling approaches developed in the previous chapters are highlighted. The usefulness of the GFPM as a forest sector tool for policy analysis is illustrated by summarizing its applications in a wide array of past and ongoing studies. These studies are summarized under four representative groups: (i) forest sector outlook studies; (ii) studies evaluating the consequences of tariff and non-tariff barriers on the international trade of forest products; (iii) studies projecting the impacts of climate change and forest-based climate change mitigation strategies on forests and forest industries; and (iv) other studies dealing with other important questions, such as the effects of the rise in global planted forest area, illegal harvests, and invasive species. Some of the limitations of GFPM, ways to mitigate these limitations, and its overall usefulness as a forest sector policy analysis tool are also examined.

The Global Forest Products Model (GFPM) offers an alternative approach to the spatial price equilibrium (SPE) trade models described in the previous chapters and the models reviewed by Latta *et al.* (2013). The GFPM is also an SPE trade model and therefore shares fundamentally similar model constructs to the Resource Economics and Policy Analysis (REPA) model. It also utilizes demand and supply equations and data on production, consumption, prices, manufacturing costs, and transport costs to maximize the sum of the consumer and producer surpluses for all products in all regions. However, the two models differ in many respects (Table 6.1) including the following.

- GFPM is calibrated using historical goal programming as opposed to positive mathematical programming in the REPA model (see Chapter 4, section 4.2, this volume).

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Table 6.1. Major differences between the REPA trade model and GFPM. (Authors' own table.)

	REPA	GFPM
Mathematical optimization	QCP/MCP solved by GAMS	QCP solved by BPMPD optimizer
Time dependency	Static model	Recursive dynamic model
Geographic coverage	Global, 20 regions	Global, 180 countries
Model calibration	Positive mathematical programming	Goal programming
Sector coverage	Eight forest products	Fourteen principal categories of forest products
International trade	Bilateral trade flows at detailed product level	Trade between country and the rest of the world[a]
Forest inventory dynamics	NA	Growth of forest inventory is a function of stocking density. Forest inventory evolves over time as previous year inventory plus projected current year growth minus harvest quantity
Forest area dynamics	NA	Rate of change of forest area in each country is projected with an environmental Kuznets curve
Base year	2016	2017 with a 3-year data average (2016, 2017, 2018)

[a] Further data are needed to model the bilateral trade flow. See Buongiorno and Zhu (2018a).

- GFPM incorporates 180 countries, while the number of regions in the REPA model is flexible and has included up to 20 regions (Chapter 4). Some regions in the REPA model are at the sub-national level, and the number of regions in the model can be expanded.
- The REPA model determines bilateral trade flows between regions, whereas individual countries trade with the aggregate world market in the standard database of the GFPM. However, GFPM can also use data sets with bilateral trade flows, as described in Buongiorno and Zhu (2018a) and as applied in Turner *et al.* (2001). An R program for integrating several countries into regions and then determining bilateral trade between the regions is provided in Appendix 4.D of Chapter 4.
- There is a difference in the number of wood products that are modeled, with 14 products in GFPM versus up to eight products in the REPA model.
- The temporal dimensions differ between the models; GFPM employs dynamic recursive solutions versus static solutions in the REPA models.
- Changes in forest resources, such as forest area and forest stock, are endogenously determined in GFPM together with endogenously projected harvests; in the REPA model, a supply function for logs is specified for each region.

Finally, the GFPM was originally developed at the University of Wisconsin-Madison during the 1990s and has subsequently been maintained and enhanced.

The objective of this chapter, however, is not to compare and contrast the GFPM with REPA models, but to describe the general model structure and the mathematical formulation of the GFPM. The objective is to introduce some representative published studies illustrating its application, as a policy tool, in evaluating different questions related to forests and the forest products sector at the national, regional, and global level so that readers interested in forest products modeling can build upon the materials, descriptions, examples, and references provided here.

In this chapter, we first provide a brief history of GFPM, followed by an overview of the GFPM's general structure. This is followed by a discussion of the data and calibration, and the validation techniques used in the GFPM, along with a detailed mathematical formulation of the model. We then highlight selected past applications of GFPM in evaluating the consequences for forest resources, forest products production, consumption, trade, and prices of various scenarios of economic and demographic changes; climate change; and changes in trade and environmental policies affecting the forest sector. We conclude by noting some of the limitations of GFPM, ways to mitigate these limitations, and its usefulness as a forest sector policy analysis tool.

6.1 A Brief History of the GFPM

The first complete version of the GFPM capable of producing long-term projections of production, consumption, imports, exports, and prices by country was developed in 1996, and was applied to produce the provisional global forest products market outlook study of the Food and Agricultural Organization (FAO, 1997). Yearly updates and improvements followed, ending with the GFPM 2017 version. The GFPM 2017 software and the latest database (3-year average data for 2016, 2017, and 2018) are provided freely at http://labs.russell.wisc.edu/buongiorno/welcome/gfpm/ (accessed September 4, 2020).

The GFPM was originally built with the Price Endogenous Linear Programming System, or PELPS (Zhang *et al.*, 1993), a general software developed to model any economic sector with spatial and temporal components, coupled with the LINDO linear programming solver (Schrage, 1991). The PELPS system itself resulted from the development of a recursive-linear programming model of the paper industry (Gilless and Buongiorno, 1987; Zhang *et al.*, 1996).

Since 1996, GFPM has been continuously improved and expanded to address various national and global issues in forest economics and policy, leading to the 2017 version of the GFPM, based on QPELPS (Quadratic Price Endogenous Linear Programming System) with the interior point BPMPD program (Mészáros, 1999), making GFPM independent of commercial optimizers.

6.2 GFPM Structure

The GFPM is designed chiefly as a policy analysis tool, facilitating an understanding of how forest products production, consumption, imports, exports, prices, and welfare are likely to change under a given or a combination of scenarios of economic changes. These include changes in gross domestic products (GDP), biophysical changes (e.g. changes in forest area, growth, and inventory), changes in technology (e.g. changes in production capacity), and changes in trade and related policies (e.g. tariff and non-tariff related trade barriers) (Buongiorno *et al.*, 2003; Buongiorno, 2015). Such a capability in GFPM is enabled through the integration of the classical four major components of forest sector models (Kallio *et al.*, 1987): timber supply (production of raw materials), processing industries (manufacturing of materials into products), demand for end products, and international trade. In obtaining the market equilibrium solution in each projected year, the GFPM follows the same theory and methods as other SPE models. That is, GFPM maximizes the global 'net social payoff' – the sum of the consumer and producer surpluses for all products and countries minus transportation costs (Takayama and Judge, 1971). This is the 'static phase' of the calculations. The 'dynamic phase' refers to the yearly changes brought about by shifts in demand that change the market equilibrium conditions, for example. Thus, the model is dynamic recursive, with no inter-temporal optimization and thus free from unrealistic 'perfect foresight' assumptions. In the GFPM the future depends only on the past and on exogenous assumptions regarding macro changes, such as GDP, population or trade policies. Technically, the model is a synthesis of econometrics, mathematical programming, and system dynamic methods (Buongiorno, 1996).

The current model deals explicitly with 180 individual countries and territories (Table 6.2), including 50 countries and territories in Africa, 47 in Asia, 37 in Europe, 22 in North America, 13 in South America, and 11 in Oceania. Country-level analysis is important for at least two reasons. First, all political decisions are by individual country governments. One exception is Canada where, under the constitution, decisions related to the forest sector are made at the provincial level. Second, checking the reasonableness of model data and output is easier at the country level than at the regional level, while more people are familiar with, say, Brazil, than with 'Latin America'. The current version of the GFPM deals with 14 forest product groups (Fig. 6.1) encompassing raw materials (industrial roundwood, other industrial roundwood, fuelwood, waste paper, and other fiber pulp), intermediate products (mechanical and chemical pulp), and end products (e.g. sawnwood, plywood, particleboard, fiberboard, fuelwood, other industrial roundwood, newsprint, printing and writing paper, and other paper and paperboard). The supply of industrial roundwood, fuelwood, and other industrial roundwood is a function of its own price and forest stock, both of which are projected endogenously. The supply of waste paper (supply of recovered paper can be constrained to satisfy a specified recovery rate) and other fiber pulps (straw, bagasse, etc.) are functions of their own prices and GDP.

The demands for the nine manufactured end products modeled in the GFPM are functions of their endogenously projected own price and an exogenously projected GDP (Buongiorno, 2015). The two intermediate products, mechanical pulp and chemical pulp, are used as inputs to paper production. Demand for raw material (industrial roundwood) and intermediate products (wood pulp) are derived from the demand for end products through the input–output coefficients

Table 6.2. Countries and territories represented in the GFPM. (Authors' own table.)

Africa		Asia	
Algeria	Madagascar	Afghanistan	Malaysia
Angola	Malawi	Armenia	Mongolia
Benin	Mali	Azerbaijan	Myanmar
Botswana	Mauritania	Bahrain	Nepal
Burkina Faso	Mauritius	Bangladesh	Oman
Burundi	Morocco	Bhutan	Pakistan
Cameroon	Mozambique	Brunei Darussalam	Philippines
Cape Verde	Niger	Cambodia	Qatar
Central African Rep	Nigeria	China	Saudi Arabia
Chad	Réunion	Cyprus	Singapore
Congo, Dem Rep	Rwanda	Georgia	Sri Lanka
Congo, Rep	Sao Tome & Principe	Kazakhstan	Syria
Côte d'Ivoire	Senegal	Kyrgyzstan	Tajikistan
Djibouti	Sierra Leone	Maldives	Thailand
Egypt	Somalia	India	Timor-Leste
Equatorial Guinea	South Africa	Indonesia	Turkey
Ethiopia	Sudan	Iran	Turkmenistan
Gabon	Swaziland	Iraq	United Arab Emirates
Gambia	Tanzania	Israel	Uzbekistan
Ghana	Togo	Japan	Viet Nam
Guinea	Tunisia	Jordan	Yemen
Guinea-Bissau	Uganda	N. Korea	
Kenya	Zambia	S. Korea	
Lesotho	Zimbabwe	Kuwait	
Liberia		Laos	
Libya		Lebanon	
Europe		**North America**	
Albania	Lithuania	Bahamas	Panama
Austria	Macedonia	Barbados	St Vincent/Grenadines
Belarus	Moldova	Belize	Trinidad & Tobago
Belgium	Montenegro	Canada	USA
Bosnia–Herzegovina	Netherlands	Saint Lucia	
Bulgaria	Norway	Costa Rica	
Croatia	Poland	Cuba	
Czech Republic	Portugal	Dominica	
Denmark	Romania	Dominican Rep	
Estonia	Russian Federation	El Salvador	
Finland	Serbia	Guatemala	
France	Slovakia	Haiti	
Germany	Slovenia	Honduras	
Greece	Spain	Jamaica	
Hungary	Sweden	Martinique	
Luxembourg	Switzerland	Mexico	
Ireland	Ukraine	Netherlands Antilles	
Italy	United Kingdom	Nicaragua	
Latvia			

Table 6.2. Continued.

Oceania		South America	
Australia	Papua New Guinea	Argentina	Guyana
Cook Islands	Samoa	Bolivia	Paraguay
Fiji Islands	Solomon Islands	Brazil	Peru
French Polynesia	Tonga	Chile	Suriname
New Caledonia	Vanuatu	Colombia	Uruguay
New Zealand		Ecuador	Venezuela
		French Guiana	

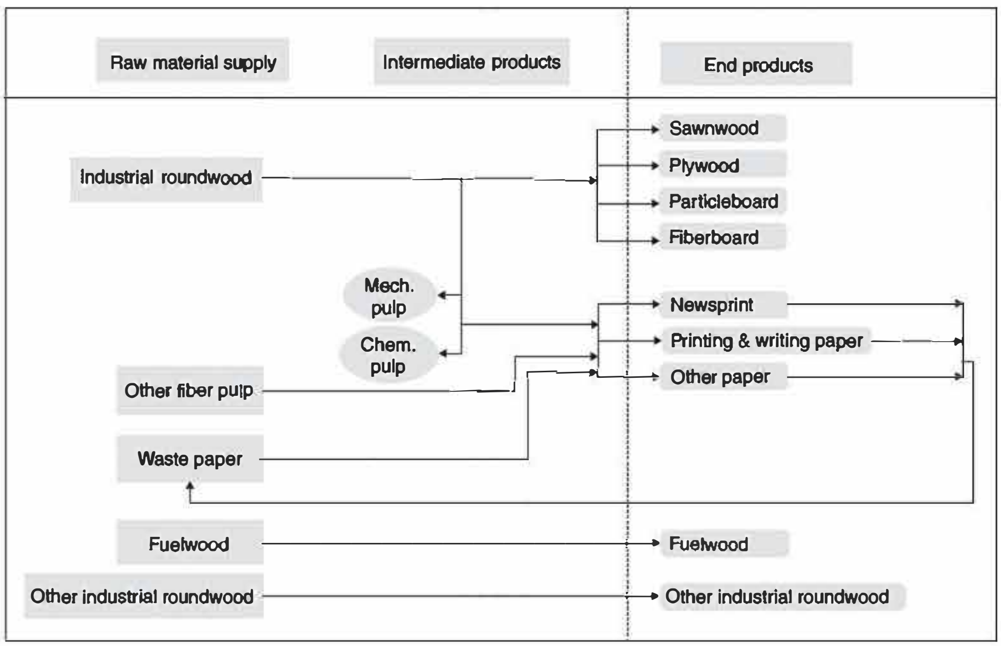

Fig. 6.1. Flow of raw materials, and intermediate and end products, as modeled in GFPM. (Authors' own figure.)

(ratio of the amount of input used in manufacturing a product to the amount of output) and manufacturing costs (labor, capital, energy). Differences in input cost, input–output efficiency, and manufacturing cost determine the comparative advantages of countries.

In the current standard data set, called the 'World file' of the GFPM, international trade (imports and exports) is between a country and the rest of the world. However, the data can be modified to represent the bilateral trade flows, as was done in Turner *et al*. (2001) and as described in Buongiorno and Zhu (2018a). Quantities of products imported or exported are driven by the competitive advantage of a country or a region in producing and shipping each product. Competitive advantage is a function of transport costs, manufacturing costs, input–output coefficients, and the endogenously determined domestic and world prices of a product. For instance, a country or a region may increase its net exports if it has a relatively more cost-effective technology (e.g. lower input requirements or lower manufacturing costs, compared with another country) in producing a particular product. In addition, changes in trade in the GFPM are limited by a priori trade inertia constraints to avoid unrealistic movements compared with historical data.

For each projected year, the model solution clears markets in all countries, obtaining prices at which demand is equal to supply for all products. The demand for end products (sawnwood, panels, pulp, and paper) in each country changes from one year to the next due to changes in GDP or up to five other exogenous demand shifters (e.g. housing construction, wood energy demand). Raw wood supply shifts according to endogenously projected changes in forest stocks or up to five other exogenously specified shifters (e.g. forest productivity due to climate change).

The forest stock shifts the supply of industrial roundwood, other industrial roundwood, and fuelwood in each country, and evolves over time as previous year stock plus projected current year growth minus harvest quantity. Forest stock growth (net of mortality) before harvest is a nonlinear function of forest stock density (forest stock per unit of forest area) based on the work by Turner *et al*. (2006). The relationship between forest growth and forest stock density implies that forest growth increases with declining stock density and decreases with increasing stock density. Changes in forest stock densities in individual countries are determined by the endogenously projected changes in forest stock and forest area. Forest area in each country is projected in the GFPM with an environmental Kuznets curve (Kuznets, 1955) originally estimated by Turner *et al*. (2006) and revised by Buongiorno (2015). The current functional form implies that forest area change is negative at low GDP per capita, becomes positive and increases at higher GDP per capita, and then decreases and approaches zero at very high GDP per capita.

Thus, the GFPM is built on the general principle that the allocation of scarce resources in the short run is optimized by global markets, while the long-run resource allocation is partly determined by the combination of market forces (e.g. projected prices) and political forces, such as changes in forest policy leading to a shift in the wood supply, changes in environmental policy affecting the wastepaper recovery, or changes in trade policies that change the cost of imports (e.g. tariff and non-tariff barriers).

6.3 Input Data, and Model Calibration and Validation

Data inputs and outputs in the GFPM are handled with Microsoft Excel spreadsheets and graphics. The GFPM needs data for the base year and the projection years. Data for the base year are mostly observed market data (e.g. quantities of production, consumption, exports and imports, and prices), biophysical data (e.g. forest stock, area), data on production technologies (e.g. input--output coefficients, manufacturing costs), and transport costs for each country, coupled with the parameters for the equations of demand, supply, manufacturing processes, and trade. Parameters of the demand and supply equations are obtained from econometric modeling (e.g. Turner *et al.*, 2006; Buongiorno, 2015). Data for the projection years are exogenously specified trajectories of demand and supply shifters or changes in other parameters.

Most of the base year data are derived from the FAOSTAT database (production, consumption, trade, and prices) and the World Bank's World Development Indicators (WDI) database (GDP and population). The data on forest stocks, forest stock growth rate, forest area, and timber growth rates are derived from the FAO's most recent Global Forest Resource Assessment. World prices are derived as the unit value of net exports (total value of net exports divided by the total quantity of net exports) as reported in the FAOSTAT database. Domestic demand and supply price of a product is equal to the world price for net exporters of the commodity, or to the world price plus freight costs and tariffs for net importers. Data on the input--output coefficients and the manufactured costs are determined simultaneously through a calibration procedure described below, which also uses the FAOSTAT data.

The purpose of the calibration procedure is to obtain a base-year model solution that matches the observed data. The calibration in the GFPM is achieved by estimating the input–output coefficients that minimize 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 input--output coefficients as suggested by technical knowledge (Buongiorno, 2015). The resulting input–output coefficients are used to further estimate manufacturing costs, which are equal to the unit value of the output minus the cost of all inputs evaluated at local prices. In calculating the manufacturing costs, world prices are used as the export prices facing the net exporter, while import prices are calculated as world prices plus transport costs and tariffs and used for the net importer countries. Thus, manufacturing costs plus other input costs (wood and other fibers) exactly offset output revenues, resulting in zero profits, as they should be in a competitive equilibrium.

The World data set available with the latest version of the GFPM (GFPM 2017) was calibrated with a 3-year data average (2016, 2017, 2018), for a base year of 2017 (Buongiorno and Zhu, 2018a). After calibration, the GFPM software checks for data consistency, ensuring that the following conditions hold for the base-year:

- Apparent consumption (production plus import minus export) equals final demand, or intermediate demand for input used by other products.
- Local price equals the world price plus the transport cost for net importers, or the world price for net exporters.
- Manufacturing cost equals the price of the output minus the cost of all inputs, given the price of inputs and the input--output coefficients.
- The waste paper used in paper manufacturing does not exceed the recovered waste paper, given the paper consumption and maximum recovery rate.

- This calibrated and consistent model is then tested with the GFPM validation procedure, which verifies that the model solution is close to the actually observed data in the base year.

More details on calibration and validation techniques are provided in the GFPM user manuals (Buongiorno and Zhu, 2018a,b).

6.4 Mathematical Formulation

In the following description, the static phase refers to the market optimization in any given year of the projection. The dynamic phase refers to the calculations that simulate periodic changes in market conditions, such as those due to economic or demographic growth.

6.4.1 Spatial global equilibrium (static phase)

The spatial competitive global market equilibrium of the forest products sector in a given year is obtained in the GFPM by maximizing the following quadratic objective function (Buongiorno, 2015):

$$\begin{aligned} \text{Maximize } Z = & \sum_i \sum_k \int_0^{D_{ik}} P_{ik}(x)dx - \sum_i \sum_k \int_0^{S_{ik}} P_{ik}(z)dz - \sum_i \sum_k \int_0^{Y_{ik}} m_{ik}(y)dy \\ & - \sum_i \sum_j \sum_k c_{ijk} T_{ijk}, \end{aligned} \tag{6.1}$$

where x, y and z are integration factors; i and j refer to countries and k refers to a product; P is price in U.S. dollars of constant value; D is final product demand; S is raw material supply; Y is quantity manufactured; m is cost of manufacture (labor, capital, and materials excluding wood and fiber); T is quantity transported; and c is freight cost (cost of transport plus tariff).

The objective function in (6.1) maximizes the total welfare in the global forest sector in a given year. It equals the surplus value of the products to consumers (consumer surplus as the area under all the demand curves above price lines) minus the cost of supplying the raw materials (quasi-rent measured as the area above the country supply curves below price).

The objective function in equation (6.1) is maximized subject to the specified constraints related to end product demand (equation (6.2)), raw material supply (equation (6.3)), wood drain (equation (6.4)), material balance (equation (6.5)), trade inertia (equation (6.6)), manufacturing costs (equation (6.7)), and transport costs (equations (6.8) and (6.9)).

Equation (6.2) specifies that the demand for each end product in each country in a given year has a constant elasticity with respect to the price, where D^* is current consumption at last period's price, P_{-1}, and δ is the price elasticity of demand. As shown in the section on the dynamic phase below, D^* depends on last period's demand, the growth of a country's GDP, and other exogenous or endogenous demand shifters.

$$D_{ik} = D_{ik}^{*}\left(\frac{P_{ik}}{P_{ik,-1}}\right)^{\delta_{ik}}. \qquad (6.2)$$

According to equation (6.3), the supply of raw materials in each country in a given year has a constant elasticity with respect to the price, where S^* is current supply at last period's price and λ is the price elasticity of supply. As shown in the dynamic phase below, S^* depend on last period's supply and on exogenous or endogenous supply shifters, especially the forest stock.

$$S_{ik} = S_{ik}^{*}\left(\frac{P_{ik}}{P_{ik,-1}}\right)^{\lambda_{ik}}. \qquad (6.3)$$

Equation (6.4) defines the total wood drain from the forest, where r refers to industrial roundwood, n to other industrial roundwood, f refers to fuelwood, $0 \le \theta_i \le 1$ is the fraction of fuelwood that comes from the forest, and $\mu \ge 1$ is the ratio of drain from forest stock to harvest:

$$S_i = (S_{ir} + S_{in} + \theta_i S_{if})\mu_i. \qquad (6.4)$$

Since the wood drain cannot exceed the available stock, the following constraint applies:

$$S_i \le I_i, \qquad (6.4')$$

where I_i is the current forest stock.

Optional constraints may limit the harvest to a fraction of the growth of forest stock, such as the 'allowable cut constraints' described in equation (6.27) below.

The next constraint defines the material balance for each country:

$$\sum_j T_{jik} + S_{ik} + Y_{ik} - D_{ik} - \sum_n a_{ikn} Y_{in} - \sum_j T_{ijk} = 0, \forall_{i,k}, \qquad (6.5)$$

where a_{ikn} is the input of product k per unit of product n. According to equation (6.5), in each country and for each product, the quantity imported, the domestic supply, and the manufactured quantity must equal the domestic demand plus the quantity used in manufacturing other products, plus exports.

In addition, the production of by-products, which results from the manufacture of a commodity (e.g. sawmill residues), can be optionally specified with the following constraints:

$$Y_{il} - b_{ikl} Y_{ik} = 0, \forall_{i,k,l}, \qquad (6.5')$$

where b_{ikl} is the by-product l that can be recovered per unit of manufactured commodity k.

Equation (6.6) defines the trade inertia constraints, introduced to quantify a dynamic adjustment process in trade in response to price and income changes.

These constraints keep the current trade quantity within a lower bound (L) and an upper bound (U), relative to the previous period:

$$T_{ijk}^{L} \leq T_{ijk} \leq T_{ijk}^{U}. \tag{6.6}$$

According to equation (6.7), the manufacturing cost is a function of manufacturing quantity. Each manufacturing process is represented by activity analysis, with input–output coefficients and a manufacturing cost. As discussed in Chapter 3, the manufacturing cost is the marginal cost of the inputs not recognized explicitly by the model (labor, energy, capital, etc.):

$$m = m_{ik}^{*}\left(\frac{Y_{ik}}{Y_{ik,-1}}\right)^{s_{ik}}, \tag{6.7}$$

where 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 dynamic phase section below, m^* depends on last period's manufacturing cost and on the exogenous rate of change of manufacturing cost.

Equation (6.8) defines the transport cost per unit of volume for commodity k from country i to country j in any given year:

$$c_{ijk} = c_{ijk}^{*}\left(\frac{T_{ijk}}{T_{ijk,-1}}\right)^{\tau_{ijk}}, \tag{6.8}$$

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

$$c_{ijk} = f_{ijk} + t_{jk}^{X}\left(P_{ik,-1}\right) + t_{jk}^{I}\left(f_{ijk} + P_{ik,-1}\right), \tag{6.9}$$

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

Upon satisfying all the constraints defined by equations (6.1) through (6.9), the shadow prices of the material balance constraints (equation (6.5)) give the market-clearing prices for each commodity and country.

6.4.2 Dynamic phase

Projections from the base year to future years are enabled in GFPM through calculation of the changes in the condition of the global equilibrium from one period to the next (referred to as the dynamic phase), as summarized in equations (6.10) to (6.24) (Buongiorno, 2015). Variables in these equations refer to one country, one commodity, and one year; the rate of change refers to a multi-year period unless otherwise indicated.

Periodic changes

Periodic exponential rates of change, r_p, are defined with annual exponential rates of change, r_a, and the length of a period in years, p:

$$r_p = (1+r_a)^p - 1 \tag{6.10}$$

Periodic linear changes, Δv_p, are defined by the annual linear change, Δv_a :

$$\Delta v_p = p\Delta v_a. \tag{6.11}$$

Demand shifts

From one period to the next, demand shifts with the exogenously specified rates of growth of the demand shifters:

$$D^* = D_{-1}\left(1+\alpha_y g_y + \alpha_0\right), \tag{6.12}$$

where g_y is the GDP periodic growth rate, α_y is the elasticity with respect to GDP, and α_0 is a periodic trend.

Supply shifts

The supplies of industrial roundwood, fuelwood, and other industrial roundwood shift periodically, according to the endogenous periodic rate of change of forest stock (g_I) and forest area (g_a), and with elasticities β_I and β_a:

$$S^* = S_{-1}(1+\beta_I g_I + \beta_a g_a). \tag{6.13}$$

Similarly, the supply of recovered paper and other fiber pulp shift periodically, according to the exogenously specified periodic GDP growth rate (g_y) and the corresponding elasticity (β_{Iy}):

$$S^* = S_{-1}(1+\beta_{Iy} g_y). \tag{6.14}$$

The periodic changes in forest area in an individual country are defined by:

$$A = (1+g_a)A_{-1}, \tag{6.15}$$

where A refers to the forest area and g_a to the periodic rate of change in forest area, which is based on the period length p (equation (6.10)), and the annual rate of change in forest area g_{aa}:

$$g_{aa} = (\alpha_0 + \alpha_1 y')e^{\alpha_2 y'}, \tag{6.16}$$

where y' refers to income per capita, which is predicted as a linear function of previous-period per capita income:

$$y' = \left(1 + g_{y'}\right) y'_{-1}. \tag{6.17}$$

For each country, α_0 is calibrated so that in the base year the observed g_{aa} is equal to the predicted g_{aa} from equation (6.16), given the income per capita y'.

Forest stocks in individual country are projected to evolve over time according to the following growth-drain relation:

$$I = \left(I_{-1} + G_{-1} - pS_{-1}\right), \tag{6.18}$$

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

At any point in time, the forest stock I equals $U \times A$, where A is the area and U is the stock density (stock per unit area). Without harvests, the stock growth rate is $dI/I = dU/U + dA/A$, or $g_I = g_u + g_a$. Therefore, stock growth without harvests is simply $G_{-1} = I_{-1}(g_u + g_a)$.

An optional exogenous adjustment, g_u^* may be added to represent, for example, the effects of invasive species or of climate change on the rate of stock growth, so that the final expression for stock growth is:

$$G_{-1} = I_{-1}\left(g_u + g_a + g_u^*\right). \tag{6.18'}$$

The periodic rate of forest growth without harvest, g_u, is based on the annual rate of forest growth without harvest, g_{ua}, and is defined by:

$$g_{ua} = \gamma_0 \left(\frac{I_{-1}}{A_{-1}}\right)^{\sigma}, \tag{6.19}$$

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 equation (6.19) given the stock per unit area, I/A.

The periodic rate of change of forest stock net of harvest, used in equation (6.13), is then given by:

$$g_I = \frac{I - I_{-1}}{I_{-1}}. \tag{6.20}$$

Changes in input–output coefficients and manufacturing costs

The input–output coefficients, a, in the material balance constraint (equation (6.5)) can change exogenously over time (e.g. to reflect increasing use of recycled paper in paper manufacturing) as follows:

$$a = a_{-1} + \Delta a, \tag{6.21}$$

where Δa is the periodic change in the input--output coefficient.

Similarly, the manufacturing cost function (equation (6.7)) can shift exogenously over time at the annual periodic exponential rate, g_m:

$$m^* = m_{-1}(1+g_m). \tag{6.22}$$

Changes in transport cost and trade inertia bounds

The transport cost function, equation (6.8), shifts exogenously over time according to equation (6.23), by recursion of equation (6.9):

$$c^* = c_{-1} + \Delta f + t^x p_{-1} - t^x p_{-2} + t^I(f + p_{-1}) - t^I_{-1}(f_{-1} + p_{-2}), \tag{6.23}$$

where $f = f_{-1} + \Delta f$, $t = t_{-1} + \Delta t$, and Δf and Δt are periodic changes in freight costs and taxes, respectively.

Finally, the lower and upper trade inertia bounds change exogenously according to:

$$T^L = T_{-1}(1-\varepsilon)^P,\ T^U = T_{-1}(1+\varepsilon)^P, \tag{6.24}$$

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

6.4.3 Modeling timber supply with carbon markets

The GFPM allows for the modeling of timber supply when wood producers are paid for leaving trees standing to sequester carbon. This is achieved with equation (6.26), which states that the marginal cost of wood in the presence of a carbon offset payment is equal to the marginal cost of harvesting and local delivery, represented in equation (6.3), plus the opportunity cost of losing the carbon payment by not leaving the trees standing. This opportunity cost is equivalent to a shift of the supply curve commensurate with the magnitude of the carbon offset payment that is introduced (Buongiorno and Zhu, 2013).

Wood supply in the absence of a carbon market is approximated as a linear function by the tangent at the current equilibrium point (P_0, S_0):

$$P = a + bS, \tag{6.25}$$

where $b = P_0/\sigma S_0$ and $a = P_0 - bS_0$. Then, wood supply in the presence of a carbon offset payment is given by:

$$P = a + bS + \varpi(P^C - P^C_{-1}), \tag{6.26}$$

where ϖ is the CO_2 content of the forest stock (tonnes/m^3), P^C is the current price of CO_2 (\$/tCO_2), and P^C_{-1} is the price of CO_2 in the previous period.

6.4.4 Allowable cut constraint

Equation (6.27) can be optionally specified in GFPM to simulate allowable cut constraints, which are in addition to the permanent constraint that limits the total wood drain from the forest to the available stock (equation (6.4′)). The allowable cut constraint in equation (6.27) states that the drain must be less than a user-specified fraction of the current annual growth of the forest stock:

$$S \leq max\,(aG/p,0), \tag{6.27}$$

where S refers to the total wood drain from the forest defined by equation (6.4), G is the periodic change in growing stock in the absence of harvest (equation (6.19)), and a is the user-defined maximum ratio of inventory drain to the growth of growing stock.

6.5 Model Calibration and Validation

The calibration procedure of the GFPM estimates input–output coefficients and manufacturing costs based on FAO data. The procedure keeps the FAO data on exports and imports unadjusted, because traded commodities typically go through custom controls at borders for compliance with laws and regulations, and are usually more reliable than production data. However, the GFPM procedure allows for adjustments of production data for any arbitrary country in any arbitrary year as reported by FAO if such data are inconsistent with prior knowledge on the possible range of the input–output coefficients (Buongiorno, 2015).

The estimated production and input–output quantities for an individual country and year are obtained with goal programming. The objective function minimizes the sum of the weighted absolute deviations between estimated production and reported production, and of the sum of the weighted absolute differences between the estimated inputs and the inputs implied by prior input–output coefficients suggested by technical knowledge:

$$minimize\ Z = \beta\sum_{k\in A} w_k(Y_k^+ + Y_k^-) + (1-\beta)\sum_{k\in I}\sum_{n\in O}(w_k w_n)^{1/2}\,(Y_{kn}^+ + Y_{kn}^-). \tag{6.28}$$

In equation (6.28) and the following equations, all variables are in capital letters and the data are in lower cases. All the variables are non-negative. The data and variables refer to a specific country and year, and the subscripts k and n refer to products. In the objective function in equation (6.28), the variables Y_k^+ and Y_k^- are the deviations of estimated input k in the production of output n above or below the inputs implied by prior input–output coefficients. The weights w_k and w_n are proportional to the product prices to allow more deviation between observed and estimated products for cheap products, and $\beta = 0.90$ to give more weight to the deviations between observed and actual production rather than to deviations between estimated and expected outputs, since FAO data are available for production but no direct data are available for the inputs in a particular output.

The objective function in equation (6.28) is minimized subject to the following constraints:

$$Y_k + Y_k^- - Y_k^+ = q_k \quad \forall k \in A \tag{6.29}$$

$$Y_{kn} - \bar{a}_{kn} Y_n + Y_{kn}^- + Y_{kn}^+ = 0 \quad \forall k \in I, n \in O \tag{6.30}$$

$$Y_k \geq X_k - Z_k \quad \forall k \in F \tag{6.31}$$

$$Y_k - \sum_{n \in O} Y_{kn} = X_k - Z_k \quad \forall k \in R \tag{6.31'}$$

$$Y_{kn} - a_{kn}^U Y_n \leq 0 \quad \forall k \in I, n \in O \tag{6.32}$$

$$Y_{kn} - a_{kn}^U Y_n \leq 0 \quad \forall k \in I, n \in O \tag{6.32'}$$

$$\sum_{k \in I} Y_{kn} - a_n^U Y_n \leq 0 \quad \forall n \in O \tag{6.33}$$

$$\sum_{k \in I} Y_{kn} - a_n^L Y_n \geq 0 \quad \forall n \in O \tag{6.33'}$$

$$Y_k - \sum_{n \in F} r_{kn}^U Y_n \leq \sum_{n \in F} (Z_n - X_n) r_{kn}^U Y_n \quad \forall k \in E \tag{6.34}$$

$$Y_k - \sum_{n \in F} r_{kn}^L Y_n \geq \sum_{n \in F} (Z_n - X_n) r_{kn}^L Y_n \quad \forall k \in E \tag{6.34'}$$

$$p_k Y_k - \sum_{n \in I} Y_{nk} p_n \leq m_k^U \quad \forall k \in O \tag{6.35}$$

$$p_k Y_k - \sum_{n \in I} Y_{nk} p_n \geq m_k^L \quad \forall k \in O \tag{6.35'}$$

Equation (6.29) defines the deviation of estimated production (Y_k) from the reported production in FAOSTAT (q_k), and A is the set of products.

Equation (6.30) defines the deviations (Y_{kn}^-, Y_{kn}^+) of the estimated input of k in product n (Y_{kn}), above or below the input expected from the prior input–output coefficients ($\bar{a}_{kn} = \frac{1}{2}\left(a_{kn}^L + a_{kn}^U\right)$; a_{kn}^L and a_{kn}^U are the lower and the upper bounds on input k per unit of output n; and I and O are the respective sets of inputs and outputs.

Constraints (6.31) and (6.31′) specify that the apparent consumption of the end products must be non-negative and that an exact equality must hold for raw materials or intermediate products used in making other products, as in constraint (6.31′). X_k and Z_k are reported imports and exported quantity, respectively, which are assumed to be error-free. F is the set of end products and R is the set of raw materials or intermediate products.

Constraints (6.32) and (6.32′) limit the estimated input–output coefficients for solidwood products (e.g. quantity of industrial roundwood per unit of sawnwood) between the prior lower and upper bounds (a_{kn}^L, a_{kn}^U), as suggested by engineering knowledge. Similarly, constraints (6.33) and (6.33′) force the estimated input–output coefficients for multiple inputs (e.g. tons of mechanical pulp, chemical pulp, other fiber pulp, and waste paper per ton of newsprint) to lie between the prior technical lower and upper limits (a_n^L, a_n^U).

Constraints (6.34) and (6.34′) specify the respective upper and the lower bounds on the recovery rates of recycled product k (e.g. waste paper) from product n (e.g. newsprint). E is the set of recycled products. Lastly, constraints (6.35) and (6.35′) specify the upper and lower bounds on the unit manufacturing costs. Variables 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, respectively.

After solving the problem specified by equations (6.28) through (6.35), the estimated input–output coefficients (the amount of product k used in making product n) are given by:

$$\hat{a}_{kn} = \frac{Y_{kn}}{Y_n} \quad \forall k \in I, n \in O. \tag{6.36}$$

The estimated input–output coefficients are used further to estimate the manufacturing costs:

$$\hat{m}_k = P_k - \sum_{n \in I} \hat{a}_{kn} P_n \quad \forall k \in O. \tag{6.37}$$

Equation (6.37) assumes a competitive market equilibrium with zero net profit so that the manufacturing cost (cost of labor and materials excluding wood and fiber and a normal return to capital) is equal to the price of the output minus the cost of wood and fiber input. Such an assumption is necessary, due to a lack of manufacturing cost data in the forest industries of most countries.

This calibration procedure is usually performed for the base year only. However, it can be replicated for earlier years to detect trends in input–output coefficients (technical change) and in manufacturing costs (Buongiorno and Zhu, 2015a). These trends are included in the GFPM 2017.

6.6 Computer Software

The GFPM integrates three different kinds of software: the Microsoft Excel spreadsheet and graphics to handle data inputs and outputs, QPELPS to set up the static and dynamic phases of the GFPM, and BPMPD (Mészáros, 1999) to calculate equilibrium in each year. The QPELPS, a general economic modeling system, takes data on the current sector state and predicted exogenous changes from a spreadsheet, writes a quadratic programming matrix expressing the GFPM static phase in MPS format, invokes the BPMPD interior point optimizer (Mészáros, 1999) to find the current year global equilibrium, updates the data to reflect this last solution and exogenous changes (dynamic phase), and starts the process again for the next period, until the time horizon is reached by successive iterations of data updating and optimization.

In the static phase, the demand, supply, and cost functions (equations (6.2), (6.3), (6.7), and (6.8)) are linearly approximated by their tangents at the current equilibrium point. Therefore, the equilibrium problem in any given year is quadratic in the objective function and linear in the constraints, and solved with BPMPD. The more time-consuming part of each periodic iteration is the data reading and updating of the dynamic phase. The most recent version of the software, the data, and the user and calibration guides are described in Buongiorno and Zhu (2018a,b) and are freely available for academic research at http://labs.russell.wisc.edu/buongiorno/welcome/gfpm/ (accessed September 4, 2020).

6.7 GFPM Application: Some Examples

With a history of more than two decades of continuous evolvement, the GFPM has found applications in numerous studies related to the national, regional, and global forest sector. These studies, which utilize the original GFPM (Buongiorno *et al.*, 2003) or its later extended versions, include several forest sector outlook reports that paint a broad picture of how the forest sector would look in the future. These projections reflect different visions of economic and demographic changes, and they typically involve scenarios of structural changes in demand or supply factors. Demand changes might include simulated shifts in the demand for particular categories of manufactured forest products (e.g. simulating the effects of more use of wood in new high-rise building construction, a decline in the demand for newsprint and printing and writing paper due to increasing internet use, etc.). Other studies deal with shocks in the supply of raw materials (e.g. due to natural catastrophes such as insect and disease outbreaks, changes in forest productivity due to climate change and CO_2 fertilization). More applications evaluate the impacts of policy-induced changes in demand and supply and forest products trade; applications include, for example, expanded use of wood for energy, increases in afforestation or reforestation to mitigate climate change, implementation of tariff or non-tariff trade barriers, and the introduction of carbon offset payment programs to encourage delayed or reduced timber harvests.

Describing all those studies is beyond the scope of this chapter. However, we present some representative examples, illustrating how the GFPM has been or is being successfully utilized to evaluate the impacts of important policy questions affecting the national, regional, and global forests and the industrial sectors that depend on them. We group these examples into four categories illustrating the wide range of applications of the GFPM: (1) long-range forest sector outlook studies; (2) assessments of the impacts of trade policies; (3) investigation of the consequences of policies aimed at climate change mitigation, including impacts of climate change on forest productivity and their effect on forest industries; and (4) miscellaneous studies.

6.7.1 Applications in outlook studies

The first application of GFPM took place in 1996 at the University of Wisconsin-Madison, on commission from the FAO. The work was done with a modified version of the PELPS system (Zhang *et al.*, 1993) and resulted in FAO's provisional outlook study (FAO, 1997), later updated in the FAO's 1999 Global Forest Products Outlook (Zhu *et al.*, 1998). These studies provided theoretically consistent projections for 180 countries in the FAOSTAT database of forest products consumption, production, trade, and prices from 1995 to 2010. Projections were based on country-specific exogenous GDP growth rates. Wood supply was price dependent, but the shifts of the wood supply functions over time were still exogenous at the time. Distinct elasticities of demand with respect to GDP and prices were estimated econometrically for high- and low-income country groups. No systematic calibration procedure had yet been found, and the input–output coefficients and manufacturing costs were estimated by Antti Rytkonen.

The GFPM was extensively used later as part of the United States Department of Agriculture (USDA) Forest Service's 2010 RPA Assessment studies, mandated by the Forest and Rangeland Renewable Resources Planning Act (RPA) of 1974. The Act requires that the U.S. Forest Service develop nationwide assessments of forest resource demand, supply and forest resource conditions every 10 years, updated every 5 years. The 2010 RPA Assessment integrated several models to project the future of forests and their industries. Two of these models were a stand-alone GFPM (Buongiorno, 2015) and its modified version, the U.S. Forest Products Model (USFPM)/GFPM (Ince *et al.*, 2011), which provides more detailed representation of wood product markets within the United States (Fig. 6.2). The USFPM/GFPM uses additional U.S. forest product demands, such as softwood lumber and hardwood lumber in contrast to a single sawnwood category in the GFPM. It also introduces more detail in U.S. forest product production, timber harvests, and timber stumpage markets (e.g. sawtimber and non-sawtimber

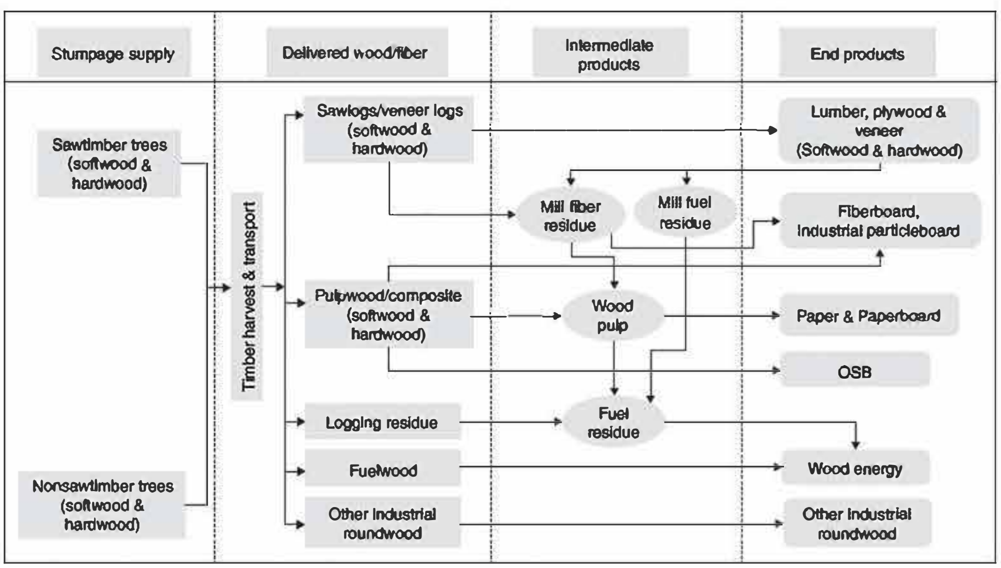

Fig. 6.2. Processes and connections among timber, delivered wood and fiber, intermediate products, and end products representing U.S. markets modeled in the modified GFPM. This modified version of GFPM is referred to as USFPM/GFPM.

harvests by hardwoods and softwood species group) for three U.S. subregions: North, South, and West. The USFPM/GFPM also simulates production of different forest-based wood biomass feedstock to meet the future increases in U.S. demand for wood energy, including roundwood fuelwood and logging and mill residues. Also important is the ability to more directly model the effects of U.S. housing construction on U.S. softwood lumber and structural and non-structural panels demand, and the effects of the displacement of graphics paper by electronic media.

One of the key policy questions in the 2010 RPA studies was how future expansion in wood energy consumption and changes in income and population would affect the forest sector in the United States and in the rest of the world. Both the standalone GFPM (Raunikar *et al.*, 2010; Buongiorno *et al.*, 2011) and the USFPM/GFPM (Ince *et al.*, 2011) were used to that end. The underlying scenarios – in particular, future changes in GDP and population – were developed in conjunction with the 4th assessment studies of the Intergovernmental Panel on Climate Change (IPCC) (Nakicenovic *et al.*, 2000) and the 2010 RPA studies (USDA Forest Service, 2012).

The approach consisted of comparing simulated projections for a reference and an alternative scenario, both of which shared exactly the same assumptions about economic drivers but differed in the projected levels of wood energy consumption. Thus, the differences in the projected outcomes between the two scenarios showed the effects on traditional forest products markets of the future changes in quantities of wood energy produced and consumed. While both the stand-alone GFPM and the USFPM/GFPM provided similar general conclusions regarding the global effects of increased wood energy (i.e. increased roundwood prices, increased lumber production, and reduced timber inventory), the results differed markedly for the U.S., mainly because of the addition of logging and mill residues in USFPM/GFPM, which satisfied the target demand for wood for energy, in contrast to the GFPM projections, which used harvested roundwood only as the wood energy source.

Another study by Ince and Nepal (2012), carried out for the 2015 Update of the 2010 RPA, employed the USFPM/GFPM to evaluate the long-term effects (to 2060) of recent trends and structural changes in U.S. forest product markets. The study included the 2007–2009 recession and recovery, a projected weakening of the U.S. dollar, and a modest increase in wood energy demand in line with historical growth rates.

In one of its most recent applications, the standalone GFPM is the main modeling tool for the 2020 UNECE Forest Sector Outlook Study (FSOS III) (Nepal and Prestemon, 2019). (The final report is expected in early 2021.) The scenarios being evaluated include five different shared socioeconomic pathways (SSPs) developed in conjunction with the fifth climate change assessment studies led by the IPCC (Riahi *et al.*, 2017). These SSPs represent alternative world visions that narratively and quantitatively describe future global changes in income, population, technology, energy use, and land-use with a varying degree of challenges for climate change mitigation and adaptation (Riahi *et al.*, 2017), consistent with global greenhouse gas and aerosol concentration trends referred to as the representative concentration pathways, or RCPs (IPCC, 2018).

The economic and demographic drivers shaping the reference scenarios adopted for the FSOS III include GDP and population (IIASA, 2018), and forest area (total forest and planted forest) projected under each SSP, by country. The projections of total forests area (Nepal et al., 2019a) and planted forest area (Korhonen et al., 2020) in each country were driven by GDP per capita and by projected rural population density and labor growth under each SSP.

Paired with the reference SSPs, different sets of alternative or policy scenarios are being evaluated to address three broad policy issues: (i) the sectoral effects of forest productivity change due to climate change; (ii) effects of climate change mitigation efforts; and (iii) the consequences of assumed structural changes in forest products markets. To evaluate the impact of climate change, exogenously projected changes in net primary productivity (NPP) are inserted in the GFPM, with parameter g_u* in equation (6.18′), whereby the endogenous growth in forest stock in each of the 180 countries is adjusted by the projected change in NPP provided by the dynamic global vegetation model MC2 (Kim et al., 2017). The projected forest and market outcomes from this run are then compared with a reference run, where no such adjustment was made to the endogenous forest growth stock. Because all other economic drivers are the same in the two runs, the differences in forest sector projections in these two runs are attributed to the changes in forest productivity induced by climate change. Similarly, the effects of climate change mitigation policies are projected by exogenously adjusting the growth rate of forest area (parameter g_{aa} in equation (6.16)) above the levels projected in the reference scenario. Lastly, the impacts of assumed future structural changes in wood products demand are simulated by exogenously shifting the demand for sawnwood, panels and paper products in the GFPM until the assumed target increases in demand are achieved in all countries.

6.7.2 Application in studies evaluating impacts of trade policies

The GFPM has also been applied in several studies of the effects of trade policies, such as multilateral trade agreements or country-specific tariffs, on the global trade of forest products, their production, their demand, and their prices. While early studies dealt with trade liberalization (Zhu et al., 2001), recent ones are more about trade restrictions. For example, Zhu et al. (2008) deals with the impact of countervailing duties on coated-free sheet paper imported by the U.S. from China, the Republic of Korea, and Indonesia. The U.S. sees some increases in producer revenues, consumer expenditures, and value added, but they are small compared with the gains in Canada.

Buongiorno and Johnston (2018a) used the GFPM to estimate the potential impact of prohibitive import barriers in the United States and of countervailing measures abroad on the economic welfare of consumers and producers in the forest sectors of the United States and of other countries. The approach consists in comparing the current state of the world with two GFPM-generated scenarios, one without U.S. imports of forest products (to represent the case of prohibitive import tariffs in the U.S.), and another without U.S. imports and also without U.S. exports (to represent the case of countervailing measures by other countries). The results suggest that implementation of prohibitive import tariffs without countervailing measures by foreign countries would result in increased U.S. producer surplus, but that such gains would not be enough to offset the loss in U.S. consumer surplus. In contrast, such measures would result in increased consumer surplus in the rest of the world, but would not be enough to offset the estimated loss in producer surplus in the rest of the world. The introduction by foreign countries of countervailing measures against U.S. exports results in increased U.S. consumer surplus at the expense of greater loss in U.S. producer surplus. For the rest of the world, such a measure increases the foreign producers' surplus, but by less than it lowers their consumers' surplus. Even without foreign retaliation, imposition of prohibitive trade barriers on U.S. forest product imports hurts U.S. consumers of forest products more than it benefits its producers, leading to a net welfare loss. A trade war, with countervailing measures against U.S. exports, further decreases welfare in the United States and abroad. Similar results were also noted in Chapter 5 using the REPA trade model.

Buongiorno *et al.* (2017) is another example of GFPM application to assess the gains and losses in the forest sector resulting from international trade. In this case, the GFPM is run in comparative-statics mode. One run of the GFPM replicates a business-as-usual situation with current trade restrictions. Another run simulates pure autarky in all countries by constraining exports and imports to zero. The results suggest that unrestricted free trade among groups of countries leads to increased global economic welfare of the forest products sector, but with unequal distribution of gains and losses in welfare, especially between high-income and low-income countries. While wood producers in developed countries increase their profits with trade, those in developing countries incur heavy losses that negate any incentive to invest in forest conservation, management and new plantations.

The impact of international trade agreements has also been the subject of GFPM applications. For example, Buongiorno *et al.* (2014) investigated the effects of the transatlantic trade and investment partnership (TTIP) on the global forest sector, based on the macroeconomic impacts estimated by other authors. Comprehensive tariff elimination per se has little effect on the forest sector. But with deeper reforms and integration, consumption increases twice as much in percentage terms in the U.S. as in the EU. Net trade decreases in the U.S. more than in the EU, while it increases in Asia. The welfare of consumers and producers increases by $7 billion in the EU and $14 billion in the U.S., but decreases in some other countries, especially in Asia.

A similar GFPM approach was used in Buongiorno and Zhu (2017) to assess the potential effects of the Trans-Pacific Partnership (TPP) potential agreement between Australia, Canada, Chile, Brunei Darussalam, Japan, Malaysia, Mexico, New Zealand, Peru, Singapore, the United States, and Vietnam (TPP12), and of an extension to include India, China, and the Republic of Korea (TPP15). The comparison with and without TTP was based on changes in GDP growth projected by macroeconomic studies. The results show that with TPP12, the main total welfare gains are in the United States and Vietnam, and the greatest losses in China and Korea. Global welfare gains are larger under TPP15 to the advantage of China, Japan, and Korea, but to the detriment of the United States, the European Union and the rest of the world.

The GFPM was also applied to forecast the effects of Brexit on the global forest products industry (Johnston and Buongiorno, 2017). One optimistic and one pessimistic scenario were used to examine the potential macroeconomic effects of Brexit. The GFPM results indicate that, with Brexit and depending on the scenario, the consumption of sawnwood in Britain would be 1.0–2.1% lower by 2030, 2.9–6.1% lower for wood-based panels, and 1.9-4.1% lower for paper and paperboard. With Brexit, the UK's net trade deficit in sawnwood decreases by 4.8–9.9% by 2030, 4.4–9.1% for wood-based panels, and 5.5–10.8% for paper and paperboard. The effects on industrial roundwood consumption and production within the UK are negligible. The consequences of Brexit are mostly within Europe and driven predominantly by reduced consumption within the UK itself. While the Brexit effects are greater under the pessimistic scenario, the overall effect on the global wood products industry is small, and it has little to no effect on global prices.

In these examples of GFPM applications to international trade, trade flows are modeled such that bilateral flows of products are not tracked, which is in line with the model set up in the standard database ('World' file) of the GFPM. However, the GFPM can also be set up to quantify bilateral trade flows. This is done by disaggregating the import and export data in the World file by country of origin and destination. For example, Turner *et al.* (2001) modified the GFPM World file to allow multilateral trade flows among the countries of AFTA–CER and P5 to evaluate the effect on the New Zealand forest sector of tariff elimination under a trade agreement among these countries. AFTA–CER refers to the Association of South East Asian Nation (ASEAN) Free Trade Area – Closer Economic Relations; the CER countries are Australia and New Zealand. The P5 countries are United States, Chile, Australia, New Zealand, and Singapore. Turner *et al.* (2001) also studied the effect on New Zealand's forest sector of tariff reductions under the World Trade Organization (WTO) administered General Agreement on Tariffs and Trade (GATT).

The GFPM has also been used to study the effects of non-tariff barriers, such as quotas (see Chapter 5), embargoes, sanctions, and export bans. For example, Turner *et al.* (2008a) assessed the effects of removing non-tariff barriers on New Zealand exports of secondary processed wood products to the United States, China, and Japan. The calculated increase in trade value from improved market access is a modest 0.0%–9.2% of New Zealand's total wood products trade by 2030. Li *et al.* (2007) used the GFPM to project the impact on the world's forest sector of curtailing roundwood trade to reduce the spread of exotic pests. With a ban on roundwood trade over 5 years, world consumer expenditures for wood products rise by 2.2% and world value added is unchanged. However, producer revenues decrease by 16% for Russia and by 10% for New Zealand. Value added decreases by 13% in Japan, 7% in Korea, and 4% in China.

6.7.3 Application in studies related to climate change issues

Key questions related to climate change and forestry that confront researchers and policymakers include the following

1. What is the potential of forests and forest industries to offset atmospheric greenhouse gases?
2. How do forest-based climate mitigation strategies (e.g. carbon offset payment leading to reduced or delayed harvests) affect the forest sector?
3. What are the effects of climate change on forest growth and productivity (e.g. due to longer growing seasons, increased CO_2 fertilization, and temperature- and precipitation-related stresses) and the attendant impacts on forest product markets?

The GFPM has been applied to investigate parts of those questions in conjunction with carbon estimating models/equations that utilize GFPM projected outputs of forest stock, forest products, consumption, trade, and prices, and with exogenous projections about climate change effects on forest productivity that serve as inputs to the GFPM in adjusting forest growth and stock and shifting timber supply. For instance, utilizing GFPM projections, Johnston *et al.* (2019) estimated the forest sector carbon mitigation potential of 180 countries during 2015–2065. The projected changes in forest carbon storage are driven by the dynamic relationships between endogenously determined roundwood harvests, forest growth and inventory, forest area, wood product consumption (domestic production plus imports minus exports), and exogenous demographic and income changes consistent with the IPPC-SPP2 scenario resembling recent historical trends. The results suggest that, while the forest sector was a carbon source in the past, it would achieve status as a net carbon sink by 2030.

Johnston and Radeloff (2019) also used GFPM to make projections, conditional on the IPCC socioeconomic pathways SSP1 to SSP5, to estimate the mitigation potential of carbon stored in harvested wood products (HWPs), including sawnwood, panels, paper, and paperboard. They found that the global HWP pool was a net annual sink of 335 Mt of CO_2 in 2015, increasing by as much as 441 Mt CO_2 per year by 2030. However, even under favorable socioeconomic conditions, carbon stored annually in HWPs is < 1% of global emissions. Furthermore, carbon stored within end-use HWPs varies widely across countries and depends on evolving market conditions.

In a similar study, Nepal *et al.* (2013a) applied the USFPM/GFPM to project changes in carbon sequestered in tree biomass and in wood products harvested from U.S. timberland. The projections are based on future forest stocks and forest products production, consumption, and trade in the U.S. under four future scenarios, including wood energy consumption, based on the IPCC's 4th Assessment and the 2010 USDA Forest Service RPA scenarios (A1B, A2, B2, and HFW). The method also demonstrates how the USFPM/GFPM market modeling system can be used to evaluate the impacts on U.S. forest carbon and forest products markets of hypothetical forest carbon offset policies, by allowing carbon offset payments to compete with traditional forest product prices (e.g. see Nepal *et al.*, 2013b,c).

Applying the same principles to global markets, Buongiorno and Zhu (2013) used the stand-alone GFPM to investigate the consequences of carbon offset payments to forestland owners. They found that offset payments of \$15–\$50 per tCO_2 applied in all countries increased CO_2 sequestration in global forests by 5–14 billion tons of CO_2 from 2009 to 2030. Limiting implementation to developed countries, environmental damage is exported from north to south, as developing countries harvest more and thereby decrease their store of CO_2. Substantially more CO_2 is sequestered by allocating a given budget to all countries rather than to developed countries only. Because offset payments increase wood prices relatively more than they decrease production, the timber revenues of forestland owners generally increase. In the few countries with timber revenues losses. they are more than compensated for by the offset payments.

In another application of the GFPM to current environmental issues, Buongiorno and Zhu (2015b) explored the long-term, *ceteris paribus* effects of potential CO_2 fertilization on the global forest sector. As input, they used the findings of Norby *et al*. (2005) about forest response to elevated CO_2. Accordingly, forest productivity is raised in the GFPM in proportion to the rising CO_2 in three alternative IPCC scenarios. Projections of forest area, forest stock and production, consumption, prices, and trade of products are projected with the GFPM for each scenario, with and without CO_2 fertilization. The main effect of CO_2 fertilization was to raise the level of the world forest stock in 2065 by 9%–10% for scenarios A2 and B2, and by 20% for scenario A1B. The rise in forest stock induced by fertilization was in part counteracted by its stimulation of the wood supply, which resulted in lower wood prices and increased harvests.

A subsequent paper by Buongiorno (2016) explored the potential long-term effects of climate warming on the global wood sector. The study used Way and Oren's (2010) synthesis, indicating positive responses of tree growth to higher temperature in boreal and temperate climates, and negative responses in the tropics. Changes in forest productivity were introduced in the GFPM, using Way and Oren's equations in accordance with the rising temperatures projected in three IPCC scenarios. Projections of forest stocks, production, prices, trade, and value added in industries were obtained with the GFPM for each scenario, with and without temperature changes from 2012 to 2065. In the three scenarios, the projected total world growing stock of forests in 2065 was hardly changed by the rise in temperature. However, the forest stock was 2%–6% higher in developed countries, while it was 3%–4% lower in developing countries. There were significant attendant changes in wood production, prices, trade, and value added in forest industries benefiting developed countries and harming the developing countries.

The GFPM approach to evaluate forest sector impacts of climate change leading to changes in productivity is also used currently to project such effects in the UNECE countries, based on the projected changes in net primary productivity in different regions under the scenario of unconstrained CO_2 emissions.

6.7.4 Application in studies related to other policy questions

Past and current versions of the GFPM have been used extensively to assess the consequences of many other policy issues regarding international forestry, forest industries, and international trade. For example, Zhu and Buongiorno (2002) applied the GFPM to project the effect of paper recycling in the United States on the international forest sector. They found that, while the United States and other major consumer countries gained in welfare, Canada and the main European producers lost. Buongiorno and Zhu (2014) and Nepal *et al.* (2019b) studied the role of planted forests in the global forest economy. Li *et al.* (2008) and Turner *et al.* (2008b) dealt with the long-term effects of eliminating illegal logging on the world forests, forest industries, and trade. Zhang *et al.* (2012) explored the domestic and foreign consequences of China's land tenure reform on collective forests. Prestemon *et al.* (2006, 2008) derived the implications for timber product markets and trade of invasive species, such as the Asian *Lymantria* in the United States.

Several studies used the GFPM in conjunction with other models to understand the carbon offset potential in the U.S. of climate mitigation strategies, such as increased use of lumber in non-residential construction (Nepal *et al.*, 2016), expanded wood energy use (Nepal *et al.*, 2015), and long-term timber set asides (Nepal *et al.*, 2013c). The GFPM has also been integrated with U.S. national and regional forest sector models to represent the competition for wood between traditional products and energy (e.g. see Nepal *et al.*, 2019c, Stokes *et al.*, 2016).

6.8 Summary and Conclusions

The purpose of this chapter was to provide a general introduction, several examples of applications, and further references about the historical development and use of GFPM. Interested readers can build upon this basis for future studies to help answer different policy questions relevant for the global, regional, and/or national forest sectors. As with the REPA trade model, one attractive aspect of the GFPM is that the software, data, and documentation are available free of charge for research. Thus, with both the REPA model and GFPM, all studies are, in principle, replicable; the basic data sets can be expanded and improved, and shared among different researchers, knowing that the method, with its strength and blemishes, is the same.

To some extent, the first part of this chapter is a short version of the full documentation (Buongiorno and Zhu, 2018a,b) of the GFPM, describing, after a brief history, the general structure, mathematical formulations, needed input data, and the techniques to calibrate and validate the model. It must be emphasized that considerable work can be and has been done with the standard data set ('World' file) available with the software and, in that case, there is no need to redo the calibration and validation. Regardless, some readers may be more interested in the representative examples of GFPM applications, with its standard data set, or as expanded by other researchers. The hope is that the examples adequately document the usefulness of the model as a policy analysis tool to encourage at least some readers to try the GFPM for their own purpose.

Four groups of representative studies have been presented to illustrate: (1) past and ongoing GFPM's application in global and national forest sector outlook studies; (2) evaluations of the consequences of tariff and non-tariff barriers in the international trade of forest products; (3) projection of the impacts of climate change and forest-based climate change mitigation strategies on forests and forest industries; and (4) miscellaneous studies dealing with other important questions such as the effects of an increase in global planted forest area, illegal harvests, and invasive species.

In evaluating these and future studies, one must keep in mind that the GFPM, like any other economic model, is only a rough representation of reality. Buongiorno *et al.* (2003) documented how historical replications, let alone future projections, can differ substantially from observation. This is especially true for international trade, which is magnified by errors in domestic supply and demand. A study of the sources of uncertainty done with a stochastic version of the GFPM indicated that parameter uncertainty was more important than errors in the initial data. Among the parameters, the errors in the supply and demand elasticities tended to dominate those of the forest area and stock equations, the input–output coefficients and manufacturing costs, and the trade inertia parameters (Buongiorno and Johnston, 2018b).

The GFPM has been criticized for too much aggregation in describing the forest resources, such as a lack of a differentiation of forest stock by species, a lack of forest age class distribution, and a lack of competition for land use between alternative uses (e.g. agricultural vs forest use). Yet, in the standard GFPM version, the endogenous rate of change of forest area follows a Kuznets environmental curve, which does simulate changes in land use on various economic development paths. Furthermore, the GFPM allows for exogenous changes in forest area, in conjunction with or instead of the endogenous Kuznets curve-dependent change. Such exogenous changes may reflect land use competition (obtained possibly from other models) that can be part of the GFPM data. This approach was followed in parts of the USDA Forest Service's 2010 RPA Assessment studies, where the USFPM/GFPM was run with the exogenously projected U.S. forest area that took into account competition for land among different uses. The GFPM software also allows for disaggregation of the forest stock by softwood and hardwood groups, as demonstrated by Ince *et al.* (2011) for the U.S. and by Schier *et al.* (2018) for all other countries.

Similarly, on the demand side, the stand-alone GFPM provides a less detailed representation of end products demand than would be desirable for some studies (e.g. the standard GFPM aggregates softwood and hardwood lumber). However, the GFPM software gives the flexibility to introduce more detailed commodities and/or products (Buongiorno and Zhu, 2018a). For instance, more detailed wood products have been added in the GFPM for the U.S. (Ince *et al.*, 2011) and for all 180 countries represented in the GFPM (Schier *et al.*, 2018).

Another difficulty lies in the estimation of the GFPM parameters. As shown above, the calibration procedure leads to input–output coefficients and manufacturing costs that differ by country. However, for lack of more data, the standard GFPM uses the same elasticities in all countries for the demand for end products (sawnwood, panels, paper, and paperboard) and the same elasticities for the supply of raw materials (wood, waste paper, other fibers). Only the intercept terms of the supply equations are calibrated for each country based on the observed base year consumption, production, and price data to ensure that the model solution replicates the base year data. However, recent work has been done to obtain country-specific demand elasticities to better fit historical data, while staying within the 95% confidence of elasticities obtained by pooling data across countries (Buongiorno, 2019). These or other country-specific, econometrically estimated demand or supply elasticities can be readily incorporated in future GFPM versions. Despite its limitations, the GFPM remains a useful tool for outlook studies and policy analysis of the forest sector, available completely and freely to all interested researchers for a wide range of applications in its standard form or with user-specific modifications.

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International Trade in Forest Products: Lumber Trade Disputes, Models and Examples

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