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An economic model of international wood supply, forest stock and forest area change

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Abstract

Wood supply, the link between roundwood removals and forest resources, is an important component of forest sector models. This paper develops a model of international wood supply within the structure of the spatial equilibrium Global Gorest Products Model. The wood supply model determines, for each country, the annual forest harvest, the annual change of forest stock and the annual change of forest area. The results suggest that global forest area would decline by 477 million ha between 1999 and 2030, with the largest decline in Asia and Africa. However, global forest stock would increase by 25 billion m^3, with the largest increase in Europe, and North and Central America. Higher global harvests and lower prices were predicted than those predicted in the past with exogenous timber supply assumptions.

Keywords: *Econometrics, forest products, forest resources, spatial equilibrium model, wood supply.*

Introduction

An important aspect of forest sector models is the description of the elements of wood supply, including forest stock, forest area and harvest volumes; both the links between these elements, and between wood supply and forest product demand. Such models enable analysis of the impact on the forest resource of policies affecting the forest industry, for example, whether or not the Free Trade Area of the Americas will result in net deforestation in Brazil (Turner et al., 2005). These models also enable assessment of the impact of changes in the forest resource on the industry; for example, what would be the impact on timber supply of accelerated forest growth in Europe due to climate change (Solberg et al., 2003).

Forest sector models describe wood supply in a variety of ways, but they generally include one or several of the following elements: timber harvest, forest stock dynamics and forest area change. Binkley (1987), Wear and Parks (1994) and Wear and Pattanayak (2003) give thorough reviews of the wood supply literature. Wood harvest has been represented by optimization or econometric models. One optimization approach uses Faustmann's formula (Faustmann, 1849) to find the economically optimal harvest age. The annual harvest volume is estimated assuming that in the long run the forest has an equal area in each age class, from zero to the optimal harvest age (Hyde, 1980). Another approach calculates short-run harvest with intertemporal optimization, as in the Timber Supply Model (TSM) (Sedjo & Lyon, 1990, 1996).

Econometric models express wood supply as a function of stumpage price, forest stock and other variables (Adams et al., 1982; Brännlund et al., 1985; Daniels & Hyde, 1986; Kuuluvainen, 1986). Stumpage price is expected to have a positive effect on wood supply, as higher prices increase the forest area that is economically accessible. Forest stock determines the short-run volume that may be harvested (Löfgren, 1984; Brännlund et al., 1985). Other variables include forest ownership types and interest rates. Econometric models are used in the CINTRAFOR Global Trade Model (CGTM) (Kallio et al., 1987; Cardellichio et al., 1989; Perez-Garcia, 1996), the Timber Assessment Market

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Model (TAMM) (Adams & Haynes, 1980, 1996) and the EFI-GTM global forest sector model (Solberg et al., 2003).

Forest stock dynamics have been represented by yield table projection or growth-drain equations (Brooks, 1987). Yield table projection describes forest dynamics in terms of the area of forest in different age classes. The forest stock in each age class is a function of the volume per unit area (forest density), which may change owing to changes in forest management. Period-to-period transition equations describe the shift of forest area from one age class to another. Harvests reduce the area in an age class, while growth shifts the area to the next age class. This approach, applied for example in the Aggregate Timberland Assessment System (Mills & Kincaid, 1992), requires knowledge of the area and yields in each age class.

The growth-drain equation (Brooks, 1987) is a more parsimonious approach that has been used in the CGTM, Tomberlin's (1999) model of timber supply in the Pacific forest sector and the EFI-GTM model. In growth-drain equations net growth may be a function of forest stock and other factors, such as climate (Brooks, 1987). However, Tomberlin (1999) and Solberg et al. (2003) use constant relative growth rates (Bull et al., 1998; Brown, 2000; Nabuurs et al., 2002). In the CGTM forest stock growth is a function of forest stock level (Binkley & Dykstra, 1987).

Few forest sector models consider forest area change, owing to the complexity of land-use decisions (Ahn et al., 1999; Barbier, 2001). The TAMM predicts forest area change with econometric equations of the proportion of land occupied by different land uses. Forest area change in regions of the USA has been studied econometrically by Alig (1986), Parks and Murray (1994), Mauldin et al. (1999) and Ahn et al. (1999). This approach is difficult to apply internationally, especially to developing countries, because of a lack of data for predictor variables, such as agricultural product prices, and land area in different uses (Barbier, 2001).

The objective of this study was to expand the wood supply module of the Global Forest Products Model (GFPM) to allow prediction of changes in country forest stock and forest area, in addition to the currently predicted harvests and prices. The next section introduces an integrated model of international wood supply, consisting of interrelated equations of timber harvest, forest growth and forest area change. The results present the parameter estimates, and their application in the GFPM to project harvest, log prices and forest resources from 1999 to 2030.

Materials and methods

Model structure

The model represents wood supply in 180 countries within the structure of the GFPM (Buongiorno et al., 2003). The theory underlying this model must be sufficiently general to cover the variety of economic situations in different countries. At the same time it must be simple enough for implementation with the scarce international data available. Accordingly, only three main variables were used to describe the wood supply in each country: annual roundwood harvest, forest stock and forest area.

In each year t, the short-run supply (harvest) of roundwood in country i is:

$$H_{it} = H_{it}^r + H_{it}^n + \theta_i H_{it}^f \tag{1}$$

where H_{it}^r is the harvest of industrial roundwood (to be transformed into sawnwood, wood panels or pulp), H_{it}^n is the harvest of other industrial roundwood (used in the round, like poles and posts), H_{it}^f is the harvest of fuelwood, and θ_i is the fraction of fuelwood harvest that comes from the forest. Each harvest component is a function of its price, forest area, forest stock and other relevant exogenous variables. The price of each component is the shadow price of the material balance constraint, equating for example the demand and supply of industrial roundwood (Buongiorno et al., 2003, p. 44). Thus, the prices are determined endogenously.

Each country's harvest also has an upper bound, independent of the price level, reflecting the amount of forest stock available for harvest:

$$H_{it} \leq S_{it} \tag{2}$$

where S_{it} is the forest stock, in volume.

The forest stock of a country is predicted with the growth-drain equation:

$$S_{i,t+1} = S_{it} + G_{it} - H_{it} \tag{3}$$

where G_{it} is the annual change in forest stock excluding harvest, obtained from the equation:

$$G_{it} = (g_{it}^a + g_{it}^u)S_{it} \tag{4}$$

where $g_{it}^a S_{it}$ is the annual change in forest stock due to forest area change, and $g_{it}^u S_{it}$ is the annual change in forest stock due to forest growth or decay on a given area. The annual relative change in forest area is a function of income per capita, $(Y/N)_{it}$, and other exogenous variables, X_{it}^a, pertaining to the environmental Kuznet's curve for forestry:

$$g_{it}^a \equiv g_{it}^a((Y/N)_{it}, X_{it}^a) \tag{5}$$

The annual relative change in forest stock due to tree growth and decay is a function of forest density, stock per unit area, $(S/A)_{it}$, and of exogenous variables pertaining to forest growth, X^s_{it}:

$$g^u_{it} \equiv g^u_{it}((S/A)_{it}, X^s_{it}) \quad (6)$$

Implementation of this model in the GFPM required estimation of three equations: the short-run timber supply for each harvest component (eq. 1), the rate of forest area change (eq. 5) and the rate of forest stock growth (eq. 6). The following sections describe the methods and data used in this estimation.

Wood supply equation

The short-run supply of industrial roundwood in country i and year t, H^r_{it}, was expressed as a function of the price of industrial roundwood, P^r_{it}; forest area, A_{it}; forest density, $(S/A)_{it}$; interest rate, r_{it}; the proportion of forest in public ownership, O_i; and the level of infrastructural development, proxied by income per capita, $(Y/N)_{it}$,:

$$\ln H^r_{it} = \beta_0 + \beta_1 \ln P^r_{it} + \beta_2 \ln(P^r_{it} O_i) + \beta_3 \ln A_{it} + \beta_4 \ln(S/A)_{it} + \beta_5 r_{it} + \beta_6 \ln(Y/N)_{it} + \varepsilon_{it} \quad (7)$$

where βs are parameters, $\varepsilon_{it} = \alpha_i + u_{it}$, the α_i are unobserved country-specific effects, and the u_{it} are time-varying effects within country i.

If supply from public forests is less price elastic than supply from private forests the effect of $P^r_{it} O_i$ will be negative. Wood supply does differ with ownership (Binkley & Dykstra, 1987; Wear & Parks, 1994; Adams & Haynes, 1996). Public forests tend to be managed for multiple uses and environmental services (Wear & Flamm, 1993), whereas private forests are managed for the financial or utility benefits of owners (Marcoullier et al., 1996; Siry & Cubbage, 2003). The result is that supply from public lands is probably less price elastic.

The effect of forest area on wood supply depends on whether there are increasing or decreasing returns to scale in harvesting (Löfgren, 1984; Johansson & Löfgren, 1985). Inclusion of forest density provides a richer description of forest capital in the wood supply model (Prestemon & Wear, 2000; Wear & Pattanayak, 2003). Other things being equal, countries with a higher forest density would be expected to harvest more, as a higher forest density implies a greater forest area in older age classes.

The opportunity cost of holding land and forest stock is captured by the interest rate. In theory, higher interest rates increase wood supply as forest owners shorten their rotation to decrease the higher opportunity cost of holding land and forest stock (Johansson & Löfgren, 1985).

Real gross domestic product (GDP) per capita, $(Y/N)_{it}$, is a proxy for a country's level of development. Higher development means better techniques and infrastructure for harvesting. The better they are the greater wood supply is likely to be, as the cost of accessing the forest and harvesting it is lower (Tomberlin, 1999).

The summary statistics for the data used to estimate eq. (7) are shown in Table I. The data were for multiple countries and for the years 1990 and 2000, the years for which international forest inventory data were available. Industrial roundwood production, H^r_{it}, (including other industrial roundwood, such as piles, piling and posts), by country, was from the Food and Agriculture Organization of the United Nations (FAO, 2001b). The trade volume weighted average unit values of imports [cost insurance freight (c.i.f.)] and exports [(free on board (f.o.b)] were used to measure industrial roundwood prices (P^r_{it}). The c.i.f. (cost insurance freight) value includes charges incurred in transporting the goods from one country to another, and the f.o.b. (free on board) is the value at the country of exportation plus loading charges only. Both values are reported by FAO (2001b) in nominal US dollars. They were converted to real prices, expressed in international dollars, to reflect purchasing power parity. The price in nominal US dollars was converted to local currency using the local exchange rate from World Bank (2003). The local GDP deflator (World Bank, 2003) was used to convert these nominal prices to real prices (base year 1987). To

Table I. Summary statistics for variables used in estimating the short-term wood supply (eq. 7).

Variable	Mean	SD	Min.	Max.	SD	
					Within countries	Between countries
Harvest volume, H^r_{it} (10^3 m^3)	26,603	68,203	5	428,452	4175	61,754
Real price, P^r_{it} (\$Int m^{-3})	246	261	30	1395	105	242
Proportion public ownership, O_i (fraction)	0.68	0.32	0.03	1.00		0.32
Real interest, r_{it} (% year^{-1})	5.78	12.35	−59.53	44.51	5.52	13.27
Forest area, A_{it} (10^6 ha)	46.97	115.44	0.07	851.39	1.84	135.53
Forest density $(S/A)_{it}$ (m^3 ha^{-1})	104.08	68.24	4.28	336.61	19.80	68.73
GDP per capita $(Y/N)_{it}$ (\$Int)	10,315	8234	411	28,726	1377	7684

Note: GDP = gross domestic product.

convert real prices in local currency to international dollars the rate of exchange of local currency to international dollars was calculated for 1990. This exchange rate was the ratio of country GDP in local currency to GDP in international dollars (both from World Bank, 2003) in 1990. The real domestic interest rate (World Bank, 2003) was the lending interest rate adjusted for inflation with the GDP deflator. Estimates of the proportion of country forest area under public ownership, O_i, in the late 1990s were from UNECE (2000) and White and Martin (2002). Y_{it} was the real GDP in international dollars. Nominal GDP statistics, in local currency, were from World Bank (2003). The local GDP deflator was used to calculate real GDP. These GDP data were converted to a common currency with the exchange rate of the local currency to international dollars in 1990. The real GDP was then divided by the country population (FAO, 2001*b*) to obtain GDP per capita, $(Y/N)_{it}$.

Forest area, A_{it}, and forest stock, S_{it}, data were from FAO (1995, 2001a). FAO (2001*a*) forest area and stock estimates are based on individual country primary technical documents. The FAO secretariat relied on these documents because they provide scientifically based data, including information on how to use them. Primary documents give data from systematic field inventories, although in most cases these were for limited areas so that estimates had to be extrapolated to the national level. For countries that had not carried out inventories, partial inventories or subjective estimates from collaboration with professionals were used by the FAO team. To compare country data, they classified estimates according to a common set of terms, and established relationships between national and global definitions.

Forest stock growth equation

The annual relative change of the forest stock for a given forest area was represented by the following model:

$$g_{it}^u = (\gamma_0 + \gamma_1 Z_i)\left(\frac{S_{it}}{A_{it}}\right)^{\alpha} + u_{it} \tag{8}$$

where Z_i is the fraction of the total forest area in plantations, α and γ are parameters and u_{it} is an error term. Relating forest stock growth to forest density (stock per unit of land, $(S/A)_{it}$) is consistent with the pattern of forest growth in forests over large areas (Oliver & Larson, 1996; Smith et al., 1996). Mature forests have a high volume per unit area and little percentage net growth in volume. Young forests have a low volume per unit area and high percentage net volume growth. Thus, α should be negative.

The variable Z_i reflects the greater productivity of plantation forests, compared with natural forests; a reason for the increasing share of timber production that comes from plantation forests (Sedjo & Lyon, 1990; Brown, 2000; Tomberlin & Buongiorno, 2000).

Data on forest stock in 1990 and 2000 (FAO, 1995, 2001a) were used to calculate the average annual percentage change in forest stock for each of 129 countries (Table II). As indicated by eqs (3) and (4), the change in forest stock between 1990 and 2000 is a result of the change in stock due to forest area change, roundwood removals and the growth of trees. The annual change in forest stock due to forest area change alone was estimated as:

$$\Delta S_i^D = \frac{\Delta A_i}{A_{i,1990}} S_{i,1990} \tag{9}$$

where $\Delta A_i = (A_{i,2000} - A_{i,1990})/10$ is the average annual forest area change from 1990 to 2000, and $S_{i,1990}$ is the forest stock, based on forest area data in FAO (1995, 2001*a*). The stock that would have existed in 2000, without change in forest area and without harvest between 1990 and 2000, was then estimated as:

$$S_{i,2000}^* = S_{i,2000} - 10 \times \Delta S_i^D + H_i \tag{10}$$

where H_i was the average annual harvest from 1990 to 2000 (FAO, 2001*b*). The annual relative change in the stock on a given forest area was then:

$$g_i^u = \left(\frac{1}{10}\right) \ln\left(\frac{S_{i,2000}^*}{S_{i,1990}}\right) \tag{11}$$

This average growth rate was then related to the average level of forest density (S_i/A_i), between 1990

Table II. Summary statistics for variables in the forest stock growth equation (eq. 8).

Variable	Mean	Median	SD	Min.	Max.
Stock growth, g_{it}^u (% year^{-1})	2.82	3.05	8.86	−20.34	32.16
Forest area, A_{it} (10^6 ha)	30	7	95	0	850
Forest stock, S_{it} (10^6 m^3)	2959	400	9978	0	82,110
Forest density, $(S/A)_{it}$ (m^3 ha^{-1})	91.83	70.96	72.06	4.55	380.90
Forest area planted, Z_i (no units)	0.12	0.03	0.21	0.00	0.90

and 2000. The proportion of each country's forests in plantations between 1990 and 2000 was calculated from data in FAO (2001a).

Forest area change equation

The forest area change equation was based on the environmental Kuznets curve (EKC). Applied to forestry, the EKC hypothesis suggests that there is an inverted U relationship between forest area loss and income per capita (Cropper & Griffiths, 1994; Koop & Tole, 1999; Vincent et al., 1997).

Estimation of the EKC followed the method of Antweiler et al. (2001) and Cole and Elliott (2003). The rate of forest area change was a function of scale, technique and composition effects. The scale effect is the result of higher consumption, and hence production, associated with increased incomes. The technique effect is the greater demand for the conservation and extension of forests, at higher incomes. The composition effect is the change in the mix of products that countries produce as incomes rise. Production of some goods increases deforestation, while others decrease it. The model also includes a measure of openness to trade interacted with variables that represent each country's comparative advantage. This allows the effect of openness to trade on forest area change to vary across countries. The complete EKC model is:

$$g_{it}^{a} = \alpha_0 + \alpha_1 (Y/N)_{it} + \alpha_2 (Y/N)_{it}^2 + \alpha_3 U_{it} + \alpha_4 (L/A)_{it} + \alpha_5 (K/A)_{it} + \alpha_6 (L/A)_{it} (K/A)_{it} + \alpha_7 \psi_{it} I_{it} + \varepsilon_{it} \quad (12)$$

with:

$$\psi_{it} \cong \psi_0 + \psi_1 (Y/N)_{it} + \psi_3 (L/A)_{it} + \psi_4 (K/A)_{it} + \psi_5 (L/A)_{it} (K/A)_{it}$$

where U is rural population density, a proxy for scale of forest use, L/A is the ratio of labour to forest area, K/A is the ratio of capital to forest area, and I is trade intensity, the ratio of the value of exports plus imports to GDP. The expression of Ψ_{it} indicates that the marginal effect of trade openness on the rate of forest area change depends on the level of the other variables.

The theory is that, other things being equal, at very low levels of income per capita Y/N, the annual relative change in forest area, g^a, is negative. As Y/N increases, g^a increases at a decreasing rate until g^a becomes zero, at which stage forest area is at a minimum. As Y/N continues to increase g^a becomes positive, reaches a maximum and then decreases towards zero, at which point forest area is maximum. Rural population density should have a negative effect. Countries with a relative abundance of capital and/or labour compared with forest area would be expected to produce goods that use forests less. The sign of the partial effect of openness to trade, I, should reflect a country's comparative advantage in forest product production. If a country has a comparative advantage in forest products, trade liberalization (larger I) should have a negative effect on forests owing to increased production of forest products for export.

The EKC was estimated with data from 58 countries in 1980, 1990 and 2000 (Table III). Estimates of country forest area were based on FAO (1995, 2001a). Forest areas in 1980 were calculated with the 1990 forest area in FAO (2001*a*) and the 1980 to 1990 forest area change in FAO (1995). The data were then expressed as an annual relative forest area change from 1980 to 1990, and 1990 to 2000, by country.

Country GDP per capita, in international dollars, for 1980 to 2000 were from World Bank (2003). The average GDP per capita from 1980 to 1990, and from 1990 to 2000 was used in estimation.

Labour per forest area, for 1980 and 1990, was based on labour force data (World Bank, 2003) and forest area data (FAO 1995, 2001a). Capital per forest area was calculated from capital per worker data ($Int per worker), for 1980 and 1990 (Summers & Heston, 1991), and the ratio of labour to forest area.

Table III. Summary statistics for variables used in forest area change (eq. 12).

					SD	
	Mean	SD	Min	Max	Within	Between
Area change, g_{it}^{a} (% year^{-1})	−0.34	1.27	−5.30	4.80	0.62	1.11
GDP per capita, $(Y/N)_{it}$ ($Int 10^3 person^{-1})	8.90	7.75	0.38	28.78	2.59	7.33
Rural population density, U_{it} (persons ha^{-1})	255	257	5	1547	27	257
Labour per forest area, $(L/A)_{it}$ (persons ha^{-1})	2.73	4.76	0.027	25.38	0.46	4.72
Capital per forest area, $(K/A)_{it}$ ($Int 10^3 ha^{-1})	48.69	101.73	0.033	612.10	14.47	100.45
Trade per GDP, I_{it} (ratio)	0.59	0.29	0.12	1.68	0.09	0.29

Note: GDP = gross domestic product.

The ratio of the value of imports and exports to GDP came from Heston et al. (2002). Countries with a large ratio are considered to be more open to trade. The average ratio from 1980 to 1990, and from 1990 to 2000, was used in estimation.

Long-term projections

The model of wood supply with attendant forest stock and forest area described above was implemented in the GFPM (Buongiorno et al., 2003; Turner, 2004). The GFPM gives long-term predictions of wood supply, processing, end-product demand and trade. Model data are available from the authors upon request.

The GFPM solves for market equilibrium by quadratic programming, based on the theory of spatial equilibrium in competitive markets (Samuelson, 1952; Takayama & Judge, 1971). The equilibrium is found by maximizing the value of the products, minus the cost of production and transportation, subject to material balance and capacity constraints in each country and each year.

The version of the GFPM used here made forecasts for 180 countries and 14 forest commodity categories from 2000 to 2030. Base-year (1999) production, consumption, trade and prices by country and commodity were from FAO (2001*b*). Base year forest stock and forest area were from FAO (2001*a*). The earlier GFPM (Buongiorno et al., 2003) expressed short-term wood supply as a function of price, as in this paper, but the supply curves shifted exogenously over time. Here, instead, the supply curves shifted endogenously in response to changes in forest stock and forest area. Forest area and stock were predicted with eqs (3)–(6), and forest harvest was predicted with eq. (1), subject to the constraint (2), with all variables being held constant, except for GDP per capita, which changed at the (exogenous) rate of GDP growth minus the rate of population growth (United Nations, 2002). The price of each wood category, the harvest, the forest stock and forest area were computed endogenously by the GFPM, simultaneously with the production, consumption, imports, exports and prices of the other products in all the countries.

The elasticities of the industrial roundwood supply with respect to GDP per capita, price and forest density came from eq. (7), with other exogenous variables assumed constant. The same elasticities were assumed for other industrial roundwood. Fuelwood supply had a price elasticity of 0.40 and a forest stock elasticity of 1.50, determined by running the GFPM from 1980 to 2000, with various elasticities and choosing those that resulted in trends most similar to the observed. The term $(\gamma_0+\gamma_1 Z_i)$ of the forest stock growth equation (eq. 8) was adjusted so that the predicted growth in 2000 was equal to the observed in 2000. In the forest area change equation (eq. 12), all variables except for Y/N were kept at their sample mean.

On the demand side, the GFPM represents demand for final products (fuelwood, other industrial roundwood, sawnwood, veneer and plywood, particleboard, fibreboard, newsprint, printing and writing paper, and other paper and paperboard) with econometric equations (Buongiorno et al., 2003). These equations relate the demand for each product to national income, measured by real GDP, and real local product price in US dollars. The GFPM determines real product price changes endogenously. Country income changes, represented by the rate of growth of real GDP from World Bank (2003), OECD (2001) and EIA (2001), are exogenous, reflecting assumptions regarding the future economic growth of each country.

Demand for raw materials (industrial roundwood, mechanical and chemical pulp, other fibre pulp and waste paper) are represented by input–output coefficients, which describe how raw materials are utilized in production, the amount of input per unit of output and the related manufacturing cost (Buongiorno et al., 2003). The input–output coefficients differ among wood products and countries, and were estimated with the methods described in Buongiorno et al. (2001).

Other assumptions and parameters of the GFPM were as in Turner (2004).

Results

Wood supply equation

The parameters of the supply equation estimated with different methods are shown in Table IV. All methods gave the theoretically expected signs, although the parameters differed substantially in magnitude.

For the pooled ordinary least squares (OLS) estimation, it was found with the Breush–Pagan test (Hsiao, 1986, p. 15) that the unobserved country effect, α_i, differed significantly across countries, leading to omitted-variable bias (Wooldridge, 2000 p. 420). Thus, the fixed effects model should be superior to the pooled OLS.

The error components estimator uses feasible generalized least squares to provide more efficient parameter estimates than fixed effects. The Hausman (1978) test, however, indicated that the unobserved country effect was correlated with the independent variables, so that the error component estimates were inconsistent.

Table IV. Parameter estimates of short-term wood supply (eq. 7), obtained by different methods.

	Method				
Variables	Pooled OLS	Fixed effects	Error component	2SLS	2SLS error component
Real price, P^r_{it} (\$Int m^{-3})	0.29 (0.21)	0.18 (0.31)	0.31 (0.13)**	1.58 (0.50)***	1.89 (1.45)
Price × Ownership, $P^r_{it}O_i$	−0.17 (0.09)*	−0.02 (0.39)	−0.25 (0.10)**	−0.27 (0.12)**	−0.34 (0.24)
Forest area, A_{it}	0.80 (0.05)***	0.20 (0.54)	0.75 (0.07)***	0.83 (0.06)***	0.81 (0.14)***
Forest density, $(S/A)_{it}$	0.71 (0.19)***	0.13 (0.11)	0.28 (0.10)***	1.10 (0.26)***	0.52 (0.29)*
Real interest, r_{it}	0.00 (0.01)	0.01 (0.01)*	0.01 (0.00)**	0.01 (0.01)	0.01 (0.01)
GDP per capita, $(Y/N)_{it}$	0.82 (0.14)***	0.29 (0.26)	0.68 (0.14)***	1.31 (0.25)***	1.39 (0.68)**
Intercept	−3.19 (2.23)	9.43 (4.62)*	0.53 (1.67)	−15.61 (5.21)***	−14.79 (14.06)
RMSE	0.98	0.23	1.05	1.29	1.52
Pooling test		26.76***	17.72***		3.94**
Hausman			28.65***		16.79**
Endogeneity[a]				11.70***	5.68*
Instrument[b]				4.29***	2.84***
				25.16***	19.67***

Note: standard errors are in parentheses.
OLS = ordinary least squares; 2SLS = two-stage least squares; GDP = gross domestic product; RMSE = root mean square error.
[a]2SLS endogeneity test F-statistic for 2SLS estimator, and chi-squared statistic for 2SLS error components estimator (Wooldridge, 2000, p. 484).
[b]t-Statistics for 2SLS instrument test (Wooldridge, 2000, p. 473).
Statistical significance: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

However, it was found that P^r_{it} and $P^r_{it}O_i$ were endogenous, so that pooled OLS, fixed effects and error components give inconsistent estimates (Wooldridge, 2000, pp. 484, 506–507). Consistent estimation of eq. (7) with two-stage least squares (2SLS) was done using country income, Y_{it}, and the interaction of country income with forest ownership, $Y_{it}O_i$, as instruments. They were valid instruments in that, after removing the effect of all other variables on P^r_{it} and $P^r_{it}O_i$, each instrument was still correlated with P^r_{it} and $P^r_{it}O_i$ (Wooldridge, 2000, p. 473). Further, Y_{it} and $Y_{it}O_i$ should not be correlated with the error term in the supply equation. This condition cannot be tested, but it is plausible.

An attempt was also made to obtain consistent and efficient estimates with the 2SLS one-way error component estimator (Balestra & Varadharajan-Krishnakumar, 1987). The pooling test (Breusch & Pagan, 1980) confirmed the need for the error components variance structure.

The preferred model was that estimated by 2SLS because it corrected for the endogeneity of P^r_{it} and $P^r_{it}O_i$ in eq. (7) and gave a price elasticity estimate with a small standard error. This model suggested that roundwood price had a positive effect on wood supply. This effect was smaller in countries with a higher proportion of forest under public ownership. The effects of forest area, forest density and GDP per capita on wood supply were all positive and significant. Only the effect of interest rate on wood supply was not significant.

Forest stock growth equation

The parameters of eq. (8), estimated by non-linear least squares (Marquardt's method, SAS Institute, 1990) are shown in Table V. All variables were statistically significant at the 0.05 level. There was a strong decline in the relative annual change of forest stock, on a given forest area, as forest density increased (Figure 1). Furthermore, for the same forest density, forests in countries with a greater proportion of forest area in plantations had a significantly higher growth rate.

Forest area change equation

The results of estimation of eq. (12) are shown in Table VI. The estimation methods were the same as for the timber supply equation, except that the 2SLS was not used because all the explanatory variables were deemed to be exogenous. The pooled OLS and error component method gave very similar results. Nevertheless, Hausman's test rejected the error component model, while the fixed effects had a very poor fit, so the pooled OLS results were adopted here.

The hypothesis was tested that more democratic countries might gain more forests or lose less than others (as better political institutions induce better forest policies) with indices from the Polity IV Project (www.bsos.umd.edu/cidcm/inscr/polity), but no statistically significant relationship was found.

Figure 2 shows the effects of income per capita on the rate of change of forest area holding all other variables constant at their sample means. Forest area

Table V. Parameter estimates of the forest stock growth equation (eq. 8).

Parameter	Estimate
γ_0	0.69 (0.22)**
α	−0.81 (0.11)**
γ_1	1.70 (0.69)**
RMSE	0.061

Note: RMSE = root mean square error.
Statistical significance: $^{**}p < 0.05$.

decreases at a decreasing rate up to an income per capita of $Int 8500. Then, forest area increases at an increasing rate up to an income per capita of $Int 20,000 when the rate of forest area increase is highest. As income continues to rise, forest area continues to increase, but at a decreasing rate. The points beyond $Int29,000 are beyond the range of the data, but they suggest that forest area would stop increasing at a per capita income of $Int 33,000. If deforestation is associated with environmental degradation and afforestation with environmental improvement, then Figure 2 is fully consistent with the EKC hypothesis.

Among other variables, rural population density had a negative, although not significant, effect on forest area change. Labour per forest area, which captured the composition effect, was significant and positively influenced forest area change, by itself and through its interaction with the openness to trade. The effect of the ratio of capital to forest area was not significant. The overall trade-induced composition effect on forest area change was significant, as shown by the F test on the variables involving I. The sign of this effect depends on the level of per capita income and relative abundance of capital and/or labour compared with forest area.

Projections to 2030

The prediction results obtained with the GFPM incorporating this timber supply model showed a decline in global forest area, from 2000 to 2030 (Figure 3). The losses for 2000–2020 were predicted to be higher than those experienced during the 1990s (FAO, 2001*a*), owing to continued forest loss in Africa and South America, and increased loss in the former USSR and Asia. From 2020 to 2030 the net loss of forest area was slower, as countries became wealthier.

Global forest stock was projected to decrease by 4 billion m^3 from 2000 to 2010, then increase 12 billion m^3 from 2010 to 2020, and 17 billion m^3 from 2020 to 2030. The largest predicted increase was in the regions with the largest share of global forest stock: South America, and North and Central America (Figure 4). European forest stock also increased, reaching 27 billion m^3 in 2020. In South America and the former USSR, the predicted forest growth was enough to compensate for the harvest and the decrease in forest area (Figure 3).

Discussion

The model of international wood supply presented here attempts to represent the mechanism of wood

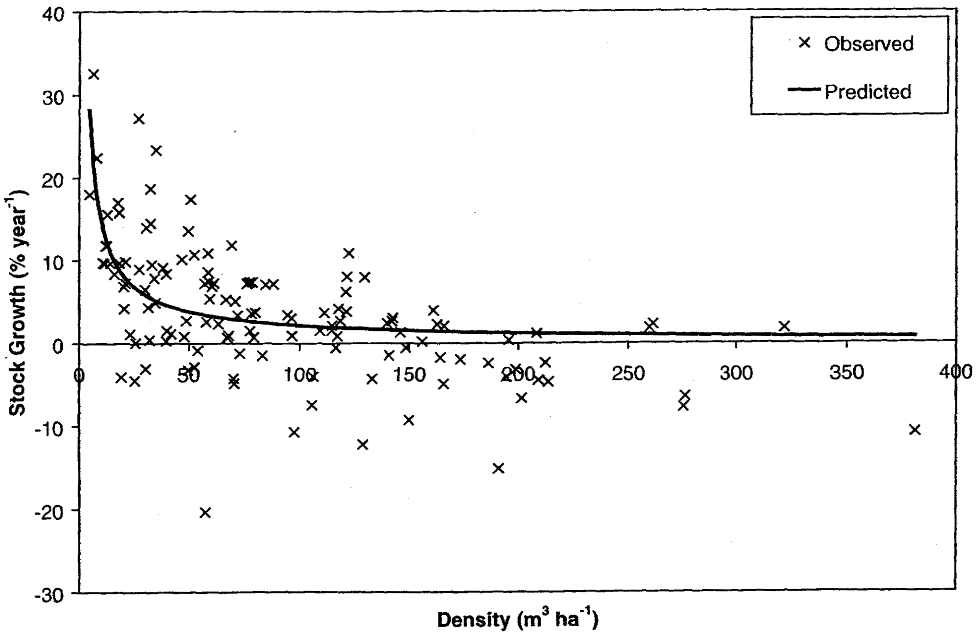

Figure 1. Relationship between forest density and forest stock growth. The predictions hold other variables constant at their sample mean.

Table VI. Parameter estimates of forest area change (eq. 12).

Variable	Pooled OLS	Error components	Fixed effects
$(Y/N)_{it}$	0.1147 (0.0510)**	0.1167 (0.0642)*	−0.0476 (0.1657)
$(Y/N)^2_{it}$	−0.0045 (0.0015)**	−0.0042 (0.0018)**	−0.0005 (0.0034)
U_{it}	−0.0009 (0.0006)	−0.0011 (0.0005)**	−0.0087 (0.0026)***
$(L/A)_{it}$	0.3440 (0.1081)***	0.3840 (0.1446)***	0.8416 (0.4478)*
$(K/A)_{it}$	0.0013 (0.0073)	0.0014 (0.0103)	−0.0134 (0.0267)
$(L/A)_{it} \times (K/A)_{it}$	−0.0002 (0.0006)	−0.0004 (0.0006)	0.0043 (0.0020)
I_{it}	−0.3927 (0.7766)	0.0303 (0.6037)	1.4198 (1.2681)
$I_{it} \times (Y/N)_{it}$	0.1221 (0.0682)*	0.1094 (0.0668)	0.1120 (0.1206)
$I_{it} \times (L/A)_{it}$	−0.2443 (0.0967)**	−0.2843 (0.1269)**	−0.3512 (0.2265)
$I_{it} \times (K/A)_{it}$	−0.0092 (0.0092)	−0.0113 (0.0131)	−0.0055 (0.0285)
$I_{it} \times (L/A)_{it} \times (K/A)_{it}$	0.0005 (0.0006)	0.0007 (0.0007)	−0.0026 (0.0018)
Intercept	−1.1594 (0.5176)**	−1.3470 (0.4785)***	−0.8989 (1.1385)
R^2	0.50	0.50	0.24
Pooling test		0.98	2.37***
Hausman test		14.69**	
Trade intensity	3.80***	11.38**	3.71**

Note: standard errors are in parentheses.
OLS = ordinary least squares.
R^2 is corrected for degrees of freedom.
Statistical significance: ***p <0.01, **p <0.05, *p <0.1.

supply in many countries. The simple theory is consistent with the scarce data available internationally. Accordingly, the wood supply model consists of econometric equations that describe short-term wood supply, the change in forest stock and the change in forest area. The short-term wood supply is a neoclassical model of supply linking harvest to price and forest stock. Forest stock changes as a result of forest area change, harvest and growth of stock on the remaining forest. Forest stock growth follows a standard yield equation tying the annual relative growth to forest density. The forest area change is an adaptation of the EKC for forestry linking forest area change to changes in wealth. The equations have been integrated into the GFPM to predict timber harvest, forest stock and forest area, simultaneously with demand, supply and trade of forest products throughout the forest sector.

According to the predictions, forest area would decline continuously from 3.9 billion ha in 1999 to 3.4 billion ha in 2030. This is an area loss greater than half the area of the USA. The largest decline

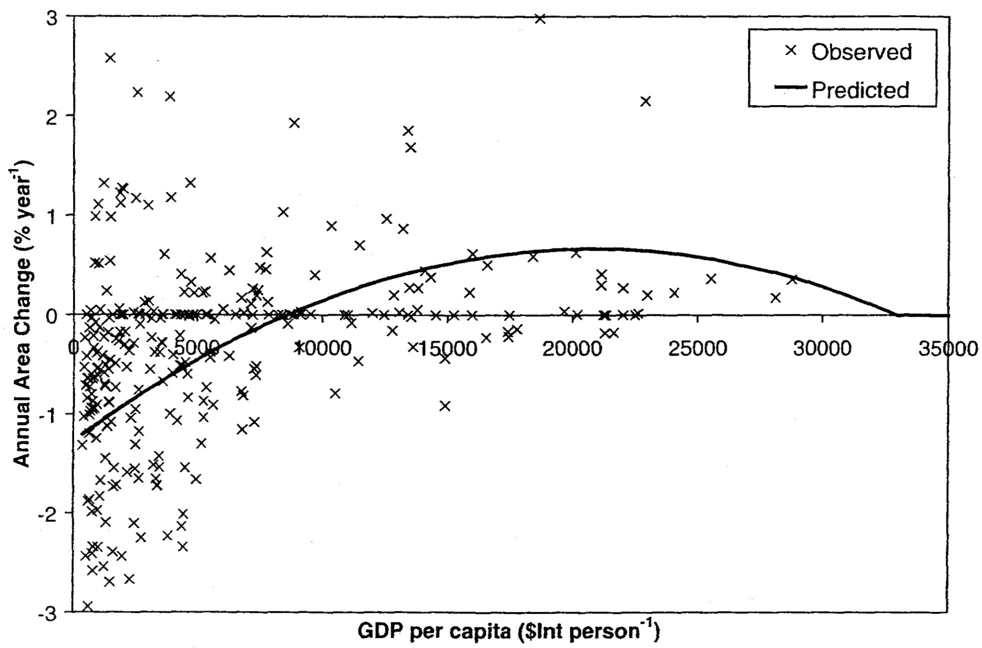

Figure 2. Predicted effect of income per capita on the annual relative forest area change. The predictions hold other variables constant at their sample mean. GDP = gross domestic product.

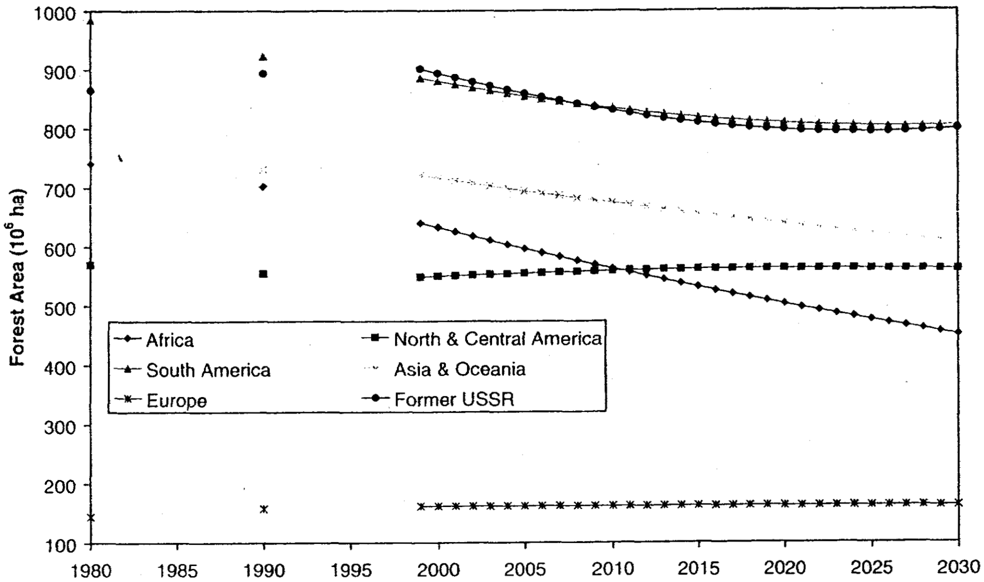

Figure 3. Historic (1980 and 1990, International Tropical Timber Organization, 2001) and projected regional forest area. Regions are defined as in Buongiorno et al. (2003).

was in Asia and Oceania, and Africa, owing to lower per capita income in these regions. This finding is in general agreement with Stern and colleagues' (1996) predictions of a global forest area decline from 4 billion ha in 1990 to approximately 3.7 billion ha from 2016 to 2025. The results of the present study were similar for 2016, but continued to decline thereafter.

Nevertheless, the predicted stock growth was enough to compensate for the harvest and the area decline in most regions, so that global forest stock would increase from 385 billion m^3 in 1999 to 408 billion m^3 in 2030, with the largest increase being in North/Central America. This compares with the 9 billion m^3 increase during the 1990s (FAO, 2001*a*). The results for Europe are similar to those of Solberg et al. (2003), who predicted an increase to 26.0 billion m^3 by 2020. The predicted slight increase in forest stock in the former USSR is counter to the view that Russian forests are "disappearing" (Rosencrantz & Scott, 1992, cited in Shvidenko & Nilsson, 1997). However, data suggest there has been an increase in growing stock in European Russia, that the decline in Asian Russia stock was due, in part, to natural disturbances, and where harvests caused decline it was most serious under

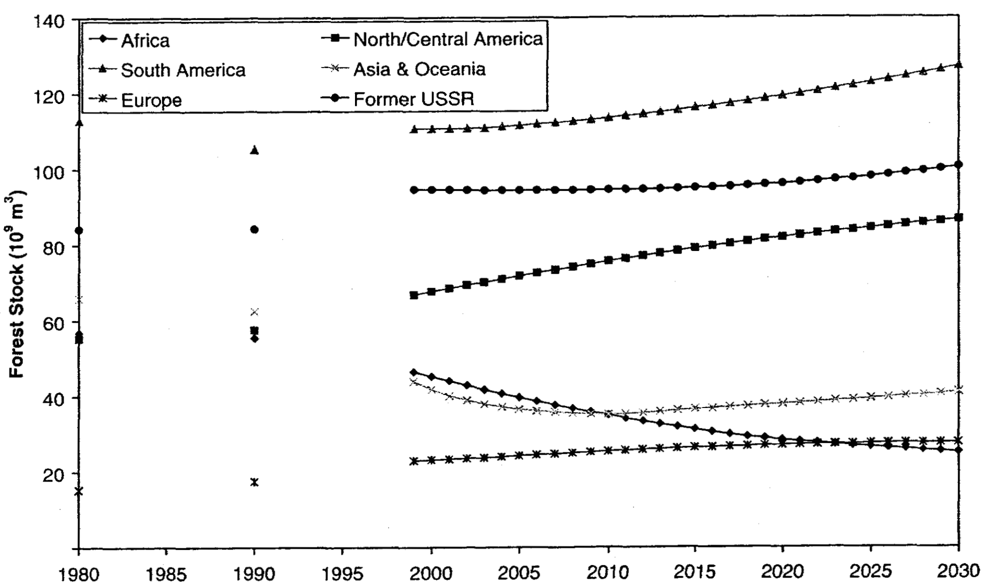

Figure 4. Historic (1980 from various sources; 1990 from FAO, 1995) and projected regional forest stock.

state forest management (Shvidenko & Nilsson, 1997). FAO (2001*a*) data indicate that the Russian Federation forest stock increased from 82.1 billion m^3 in 1990 to 89.1 billion m^3 in 2000.

The introduction of an endogenous timber supply had significant effects on predictions of timber harvest and prices. Figure 5(a, b) show historical trends and projections of industrial roundwood harvests, from the GFPM with the wood supply model presented in this paper, and with exogenous wood supply shifts (Buongiorno et al., 2003). The harvest predicted with endogenous timber supply was higher in North/Central America, South America, Europe and the former USSR. This is due to the endogenous supply shifts, caused by increases in forest stock, being greater than the exogenous supply shifts from Buongiorno et al. (2003). In Africa, and Asia and Oceania predicted harvests were lower, owing to forest stock decline reducing timber supply in these regions.

Figure 6 presents historical trends and projections for the price of industrial roundwood, in 1997 US dollars, at the world level, measured by the unit value of exports. The world price predicted with the endogenous timber supply was much lower than that predicted with the exogenous supply shifts (Buongiorno et al., 2003). This reflects the rise in forest stock, and the attendant higher supply predicted with the endogenous timber supply, especially in North America, South America and Europe. Thus,

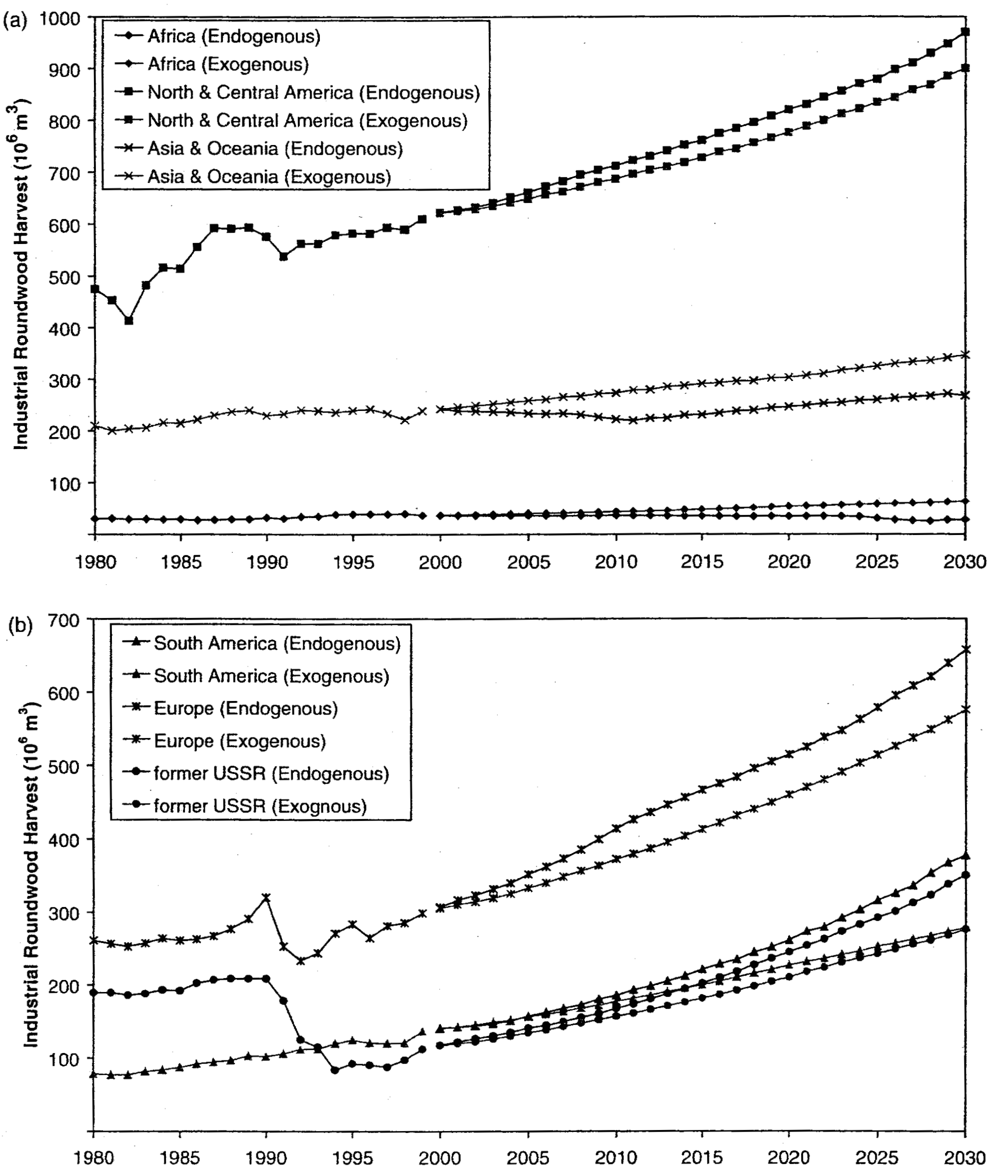

Figure 5. Historic (FAO, 2001b) and projected regional industrial roundwood harvest, using the Global Forest Products Model with and without endogenous timber supply. (a) Africa, Asia and Oceania, North and Central America; (b) Europe, former USSR and South America.

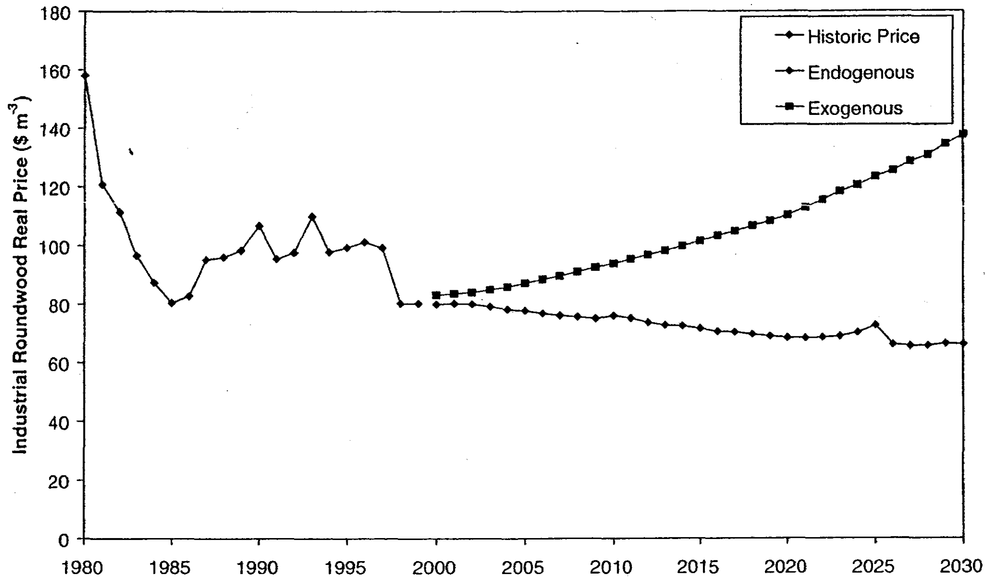

Figure 6. Historic (FAO, 2001b) and projected world real industrial roundwood price.

the exogenous supply shifts assumed previously seem to have underestimated the increase in timber supply that is likely to occur in the future.

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