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Joseph Buongiorno[a] & Sushuai Zhu[a]

[a] Department of Forest and Wildlife Ecology, University of Wisconsin-Madison, Madison, WI, USA

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RESEARCH ARTICLE

Technical change in forest sector models: the global forest products model approach

Joseph Buongiorno* and Sushuai Zhu

Department of Forest and Wildlife Ecology, University of Wisconsin-Madison, Madison, WI, USA

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Technical change is developing rapidly in some parts of the forest sector, especially in the pulp and paper industry where wood fiber is being substituted by waste paper. In forest sector models, the processing of wood and other input into products is frequently represented by activity analysis (input–output). In this context, technical change translates in changes over time of the input–output (I–O) coefficients and of the manufacturing cost (labor, capital, and materials, excluding wood and fiber). In the case of the global forest products model, the I–O coefficients and the manufacturing costs are determined empirically from historical data, while correcting for possible reporting errors. The method consists of goal programming. The objective function is the sum of the weighted absolute value of the deviations from estimated and observed production in each country of interest. The constraints express the relationship between the multiple output (sawnwood, panels, pulp, paper) and input (wood, waste paper, other fiber) and prior knowledge on the limits of the I–O coefficients. The paper presents observed technical changes from 1993 to 2010 and projections to 2030 with their consequences for the global forest sector in terms of prices, production and consumption, value added, and carbon sequestration in forest biomass.

Keywords: technical change; international; demand; supply; cost; GFPM

Introduction

In the context of economic modeling, technical change refers to changes in the efficiency of transforming inputs into products. There are few studies dealing with technical change in forest sector models, especially at an international level. The purpose of this paper is to help fill this gap. It does this in two ways: first by offering a new general method to describe the production techniques in activity-analysis models. The method, based on goal programming, estimates national input–output (I–O) coefficients and attendant manufacturing costs from standard production and trade statistics published by international agencies (e.g. FAO 2013), while recognizing that some of the data may be inaccurate. Second, the paper applies this method in a specific model of the global forest sector with 180 countries (global forest products model [GFPM], Buongiorno et al. 2003) to measure the extent of past technical change, and to then to project its future impact on international prices, production, consumption of forest products, value added, and carbon sequestration in forests.

Early quantitative studies of technical change in forest industries relied on econometric analysis at an aggregated level, measuring technical change as a residual, or bias, after the effect of other inputs (labor, capital, and some materials) were accounted for. Stier and Bengston (1992) give a thorough review of these studies, done with diverse functional forms ranging from Cobb-Douglas to translog production or cost functions, for several forest product industries and regions.

Contemporary models of the forest sector have attempted to refine the representation of the production processes in the various subsectors, such as sawmilling and pulp and paper, with activity analysis, whereby the techniques of production are represented with I–O coefficients and attendant costs (Hazell & Norton 1986; Dykstra & Kallio 1987). Current forest sector models of this kind include the European Forest Institute-Global Trade Model (EFI-GTM; Kallio et al. 2004), the Forestry and Agricultural Sector Optimization Model (FASOM; Adams et al. 1996), the Global Biosphere Management Model (GLOBIOM; Lauri et al. 2013), and the GFPM (Buongiorno et al. 2003). The latter is used below as an example, although the methods could be used for other models with a similar representation of production.

There is a large literature on technical change in I–O analysis, some of which is highly theoretical (e.g. Craven 1983). In contrast, Rose (1984) identifies 12 empirical methods. They range from "ex-ante" approaches, asking experts to project changes, in addition to current coefficients, as was done for example in the original version of the GFPM (Zhang et al. 1997), to extrapolation and nonlinear I–O allowing for endogenous input substitutability.

The procedure described below maintains linearity and extrapolation, while using "ex-ante" engineering

*Corresponding author. Email: jbuongio@wisc.edu

information as a limiting constraint. Thus, the concept is similar to that of Wilting et al. (2008) which combines data-based trend analysis with engineering knowledge. It follows Leontief's (1989) precept to combine "theoretical analysis with factual information," by using all the international data available on the forest sector, in the form of the complete Food and Agriculture Organisation Statistics (FAOSTAT) database (FAO 2013).

The present method is also akin in spirit, but not in actual procedures, to the principles of "grey" systems analysis, in particular grey dynamic I–O analysis (Li 2009), in which part of the system information is known, and part of it is unknown. In the case of the GFPM and analogs, we usually have data on national production and trade, and some information on prices (from the import and export unit values), but little information on I–O coefficients and manufacturing costs. In addition, the FAOSTAT data are subject to errors. For example, in some countries, the apparent consumption (production plus imports minus exports) of industrial roundwood does not agree with the production of sawnwood and pulp products, and the apparent consumption of wood pulp and other fiber pulp does not agree with the production of paper and paperboard (Buongiorno et al. 2001). The approach offered here has the advantage of relying only on the widely used methods of goal programming (e.g. Hillier & Lieberman 1990, p. 27; Winston 1991, p. 732) and on standard international statistics (e.g. FAO 2013) coupled with readily available engineering knowledge of production techniques. Applied to the global forest sectors, it leads to previously unavailable data concerning the extent of technical change and its potential future impact.

The remainder of the paper is organized as follows. The next section presents how technical change is modeled in the GFPM. This is followed by the method used to estimate I–O coefficients and attendant manufacturing costs in different countries and over time. The past technical change obtained with this method from 1993 to 2010 is then presented for each subsector, and this is followed by the projections of technical change from 2010 to 2030. Next we present the consequences of this future technical change on industrial roundwood utilization, the substitution of wood pulp by waste paper, the effects for the value added in industries, and the amount of carbon stored in growing stock. Last, the discussion deals with the pros and cons of the method and possible directions for further research.

Materials and methods

Representation of technical change in the GFPM

The GFPM is a dynamic, recursive partial equilibrium model of the world forest sector. Starting from an initial condition in the base year, 2010 in the GFPM version 2013, it simulates changes in forest stock and area, and in production, consumption, prices, and trade of 14 groups of forest products in 180 countries. The changes from year to year are driven by the exogenous growth of gross domestic product and population. In each projected year, the model assumes competitive spatial market equilibrium within the forest sector. The equilibrium is computed by solving the following optimization problem which assumes perfect competition and perfect substitution of products from different origins (Samuelson 1952; Takayama & Judge 1971):

$$\max\left(\sum_{i,k}\int_0^{D_{i,k}} P_{ik}(D_{ik})dD_{ik} - \sum_{i,k}\int_0^{D_{i,k}} P_{ik}(S_{ik})dS_{ik} - \sum_{i,k}\int_0^{D_{i,k}} m_{ik}(Y_{ik})dY_{ik} - \sum_{i,j,k} c_{ijk}T_{ijk}\right) \quad (1)$$

Subject to:

$$\sum_j T_{jik} + S_{ik} + Y_{ik} - D_{ik} - \sum_n a_{ikn}Y_{in} - \sum_j T_{ijk} = 0 \qquad \forall i,k \quad (2)$$

where the variables, all non-negative, are defined as follows:

P_{ik} : price of product k in country i.
D_{ik} : demanded quantity of end product k in country i.
S_{ik} : supplied quantity of raw material k in country i.
Y_{ik}, Y_{in} : manufactured quantity of products k or n, respectively, in country i.
T_{ijk} : quantity of product k transported from country i to country j.

And the parameters are:

m_{ik}: manufacturing cost (labor, capital, and materials, excluding wood and fiber) of product k in country i.
c_{ijk}: transport cost per unit of product k from country i to country j, including tariff and taxes.
a_{ikn}: input in country i of product k per unit of output n.

Thus, the first integral in the objective function (1) is the value of the end products to consumers, the second and the third the cost of production, and the last part is the transport cost. The optimization is carried over the variables D_{ik}, S_{ik}, Y_{ik}, and T_{ijk}, subject to the demand–supply constraints. The left part of each constraint is the sum of the imports, domestic supply, and manufactured quantity of a product in a country minus the sum of the domestic demand for the end products, the demand for input in manufacturing other products, and the exports to other countries. The primal solution of (1) and (2) gives the quantities consumed, produced, and traded, while the dual solution gives the equilibrium price, P_{ik}, for each product and country.

Within this model, the wood supply is represented by econometric equations (Turner et al. 2006). The techniques of production to transform wood into intermediate and end products in a particular year are defined by the I–O coefficients, a_{ikn}, for the input and products explicitly recognized in the model (roundwood, sawnwood, wood-based panels, pulp, paper, and paperboard) and by the manufacturing cost, m_{ik}, the cost of other input (labor, capital, and materials, excluding wood and fiber). For the purpose of this paper, technical change then refers to changes over time of these I–O coefficients and attendant manufacturing costs.

Estimation of the I–O coefficients and manufacturing costs

The I–O coefficients, a_{ikn}, and manufacturing costs, m_{ik}, of the GFPM are determined simultaneously by a calibration procedure based on Buongiorno et al. (2001). Each I–O coefficient in a year and country is the ratio of the amount of input used in manufacturing a product to the amount of output. However, no systematic international data exist on how much, say, mechanical or chemical pulp is used in a country to make newsprint, and although there are data on the total production of each product they are typically imprecise. The procedure estimates the amount of input going into an output while adjusting the total production of the input or output if needed. This then provides an estimate of the I–O coefficients, which together with data on local prices give an estimate of the manufacturing costs.

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

In the following goal-programming formulation, of which an example is given in the appendix, all the variables and data refer to a specific country and year.

Variables, all non-negative:

Y_k, Y_n : estimated production of product k or n, respectively.
Y_k^+, Y_k^- : deviation of estimated production of product k above or below the production reported in FAOSTAT.
Y_{kn} : estimated input of product k in product n.
Y_{kn}^+, Y_{kn}^- : deviation of estimated input of product k in product n above or below the input implied by prior I–O coefficients.

Data:

q_k, m_k, x_k: production, imports, and exports of product k, reported in FAOSTAT.
p_k, p_n : local price of product k or n, respectively.
a_{kn}^L, a_{ikn}^U : lower, upper bound on input k per unit of output n.
$\bar{a}_{kn} = (a_{kn}^L + a_{kn}^U)/2$: expected input k per unit of output n.
a_n^L, a_n^U : lower, upper bound on total inputs per unit of output n.
r_{kn}^L, r_{kn}^U : lower, upper bound on amount of recycled product k per unit of product n.
m_k^L, m_k^U: lower, upper bound on unit manufacturing cost of product k, the cost of all other input (labor, capita, energy), excluding the cost of wood and fiber.
β : weight of deviations from reported production relative to the weight of deviations from expected input.
w_k, w_n : weight of deviations of estimated from reported production and of estimated from expected input, for product k and n, respectively.
A : set of all products.
I : subset of inputs.
O : subset of outputs.
F : subset of final products.
R : subset of raw materials or intermediate products.
E : subset of recycled products.

The objective function is:

$$\min \beta \sum_{k\in A} w_k(Y_k^+ + Y_k^-) + (1-\beta) \sum_{k\in I} \sum_{n\in O} (w_k w_n)^{1/2}(Y_{kn}^+ + Y_{kn}^-) \quad (3)$$

Subject to:

Deviation of estimated production from reported production:

$$Y_k + Y_k^- - Y_k^+ = q_k \qquad \forall k \in A \quad (4)$$

Deviation of estimated input of product k in product n from expected input:

$$Y_{kn} - \bar{a}_{kn} Y_n + Y_{kn}^- - Y_{kn}^+ = 0 \qquad \forall k \in I, n \in O \quad (5)$$

Material balance:

$$Y_k - \sum_{n\in O} Y_{kn} = x_k - z_k \qquad \forall k \in R \quad (6)$$

$$Y_k \geq x_k - z_k \qquad \forall k \in F$$

Bounds on input k in output n:

$$Y_{kn} - a_{kn}^U Y_n \leq 0 \qquad \forall k \in I, n \in O \quad (7)$$

$$Y_{kn} - a_{kn}^L Y_n \geq 0 \qquad \forall k \in I, n \in O$$

Bounds on total inputs in output n:

$$\sum_{k\in I} Y_{kn} - a_n^U Y_n \leq 0 \qquad \forall n \in O \tag{8}$$

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

Bounds on product recycling:

$$Y_k - \sum_{n\in F} r_{kn}^U Y_n \leq \sum_{n\in F} (z_n - x_n) r_{kn}^U \qquad \forall k \in E \tag{9}$$

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

Bounds on manufacturing cost:

$$p_k Y_k - \sum_{n\in I} Y_{nk} p_n \leq m_k^U \qquad \forall k \in O \tag{10}$$

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

In current applications (Buongiorno & Zhu 2013), the weights w_k and w_n are commensurate with the product prices (see example in appendix) to allow more deviation between observed and predicted production for cheap products, and $\beta = 0.90$ to give more weight to the deviations between observed and actual production than to deviations between estimated and expected input, because data (possibly imprecise) are available for Y_k and Y_n but no direct data exist for Y_{kn}.

The constraints (4) define the deviations of the estimated production from the reported production in FAOSTAT. The constraints (5) define the deviations of the estimated from the expected input in each output, given the prior I–O coefficients. The constraints (6) specify that the apparent consumption of the end products must be non-negative (exact equality must hold for raw materials or intermediate products used in making other products). The reported imports and exports, z_k and x_k, are assumed to be error-free in current applications, as they usually go through customs and thus may be more reliable than production data.

The constraints (7) keep the estimated I–O coefficients, such as the amount of industrial roundwood per unit of sawnwood, between prior upper and lower bounds suggested by engineering knowledge. In addition, the constraints (8) express the fact that for paper and paperboard the total amount of the different fibers (mechanical pulp, chemical pulp, other fiber pulp, waste paper) used in manufacturing a ton of product, must also lie between prior technical limits, a_n^L, a_n^U, the lower and upper amount of total fiber used per unit of product n. The constraints (9) express the feasible post-consumer recovery, such as the maximum amount of paper and paperboard that can be recycled, where r_{kn}^U is the upper bound on the recovery rate of product k (say waste paper) from product n (say newsprint). The last constraints (10) refer to the upper and lower bounds on the unit manufacturing cost.

After solving the problem specified by Equations 3–10, the estimated I–O coefficients, $\hat{a}_{kn}$, the amount of product k used in making product n, are given by:

$$\hat{a}_{kn} = \frac{Y_{kn}}{Y_n} \qquad \forall k \in I, n \in O \tag{11}$$

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

$$\hat{m}_k = p_k - \sum_{n\in I} \hat{a}_{nk} p_n \qquad \forall k \in O \tag{12}$$

where the prices, p_k and p_n, are the world prices (unit values of world exports) for net exporters and the world prices plus the transport costs and tariffs for net importers. The strong assumption underlying this definition of manufacturing cost was predicated by the paucity of international data on manufacturing costs in forest industries.

Any deviation of the estimated value of production from the reported value in the FAOSTAT database is revealed by a positive value of the deviational variables, Y_k^+ for an overestimation or Y_k^- for an underestimation.

An example of calibration data and results is given in the Appendix. With I–O coefficients and manufacturing costs determined in this way for each country, and the end-product demand and wood supply equations positioned with the price and quantity in each country, the solution of the global equilibrium expressed by equations (1) and (2) closely replicates the input data that result from the calibration, in terms of production, consumption, net trade, and prices.

Results

Past technical change, 1993–2010

The technical changes embedded in the GFPM version 2013 were based on estimated I–O coefficients and attendant manufacturing costs from 1993 to 2010. To this end, the calibration expressed by Equations 3–12 was redone for all the 180 countries in the GFPM and for each year from 1993 to 2010, after smoothing the data from 1992 to 2011 with a three-year moving average. Smoothing was meant to better approximate equilibrium conditions and to reduce the effect of data errors in the FAOSTAT. The calibration software of the GFPM automates the downloading of the FAOSTAT data and the generation of time series of I–O coefficients and manufacturing cost (Buongiorno & Zhu 2013). The weights, bounds on the I–O coefficients, recovery rates, and manufacturing cost were the same for all countries and for all years.

Table 1. Differences between reported and estimated production in 2010.

Commodity	World production		Difference across countries (%)		
	Reported (10^3 m^3)	Estimated (10^3 m^3)	Average	SE	*N*
Industrial roundwood	1358,199	1425,982	4.4	1.8	170
Sawnwood	390,290	390,321	0.0	0.0	180
Veneer and plywood	96,749	97,301	2.6	2.6	178
Particleboard	94,386	94,390	0.0	0.0	178
Fiberboard	90,070	90,071	0.0	0.0	179
	(10^3 t)	(10^3 t)			
Mechanical pulp	29,733	31,435	0.5	0.3	153
Chemical pulp	135,489	136,165	1.2	1.2	156
Other fiber pulp	17,729	23,176	8.2	5.1	108
Waste paper	206,264	206,883	1.1	0.3	140
Newsprint	33,312	33,332	0.0	0.0	176
Printing and writing paper	110,919	111,032	0.0	0.0	174
Other paper and paperboard	250,588	250,619	0.0	0.0	176

SE, standard error; *N*, number of producing countries in 2010.

Table 1 summarizes the differences between the production statistics reported in FAOSTAT and those calibrated for 2010, for the world total, and across countries. The differences were larger for the raw materials and intermediate products than for the end products. The largest differences were for other fiber pulp (made from fibrous vegetable materials other than wood) and industrial roundwood, for which the estimated production exceeded the reported on average by 8.2% and 4.4%, respectively. However, the estimates nearly matched the reported data for sawnwood, particleboard, fiberboard, newsprint, printing and writing paper, and other paper and paperboard.

Figure 1 shows the evolution from 1993 to 2010 of the mean, over all countries, of the industrial roundwood input per unit of product, and the standard error of the mean. Also shown is a linear trend line fitted by least squares to the average data. From 1993 to 2010, there was a decrease of the amount of industrial roundwood per unit of product, except for mechanical pulp. For example, the world average of industrial roundwood per unit of sawnwood declined by 0.003 m^3/m^3/year over the period. The change in I–O coefficient was statistically significant at least at the 0.10 level for all products (Table 2). Figure 2 shows parallel data for the amount fiber per unit of newsprint. While the input of mechanical and chemical pulp declined, the input of other fiber pulp and waste paper increased. The statistically significant trends were the decrease of chemical pulp at 0.003 t/t/year, which was exactly compensated by the increase of waste paper (Table 2).

For printing and writing paper (Figure 3), the decrease of mechanical pulp input was more pronounced than for newsprint, and it was accompanied by a decrease in chemical pulp input. Both trends were statistically significant (Table 2), while there was hardly any change in the input of other fiber pulp and waste paper.

In the case of other paper and paperboard (Figure 4), the significant trends were declines in the use of mechanical and chemical pulp, each at a rate of 0.001 t/t/year. This was compensated exactly by an increase of waste paper input of 0.002 t/t/year, all statistically significant, while there was no change in the input of other fiber pulp (Table 2).

The past trends in the manufacturing cost of solid wood products are summarized in Figure 5 which shows the mean manufacturing cost over all the countries that made the product, plus or minus one standard error. In the solid wood subsector, from 1993 to 2010 there was little systematic change in the manufacturing cost of sawnwood. Instead, the manufacturing cost of plywood, particleboard, and fiberboard increased significantly, at rates ranging from \$4/m^3/year to \$8/m^3/year (Table 3).

Within the pulp and paper subsector, the manufacturing cost increased for mechanical, chemical pulp, and other paper and paperboard (Figure 6), at rates that were all statistically significant and ranging from \$4/t/year to \$7/t/year. However, during the same period, the manufacturing cost of newsprint and printing and writing paper decreased at statistically significant but smaller rates of \$2/t/year to \$3/t/year (Table 3).

Projected technical changes, 2010–2030

As observed from the stability of the standard errors over time in Figures 1–6, there was little systematic trend in the variation of the I–O coefficients or of the manufacturing costs across countries. Consequently, it was assumed in the GFPM version 2013 that technical change would continue to evolve in all countries in parallel with the average world trend until 2030.

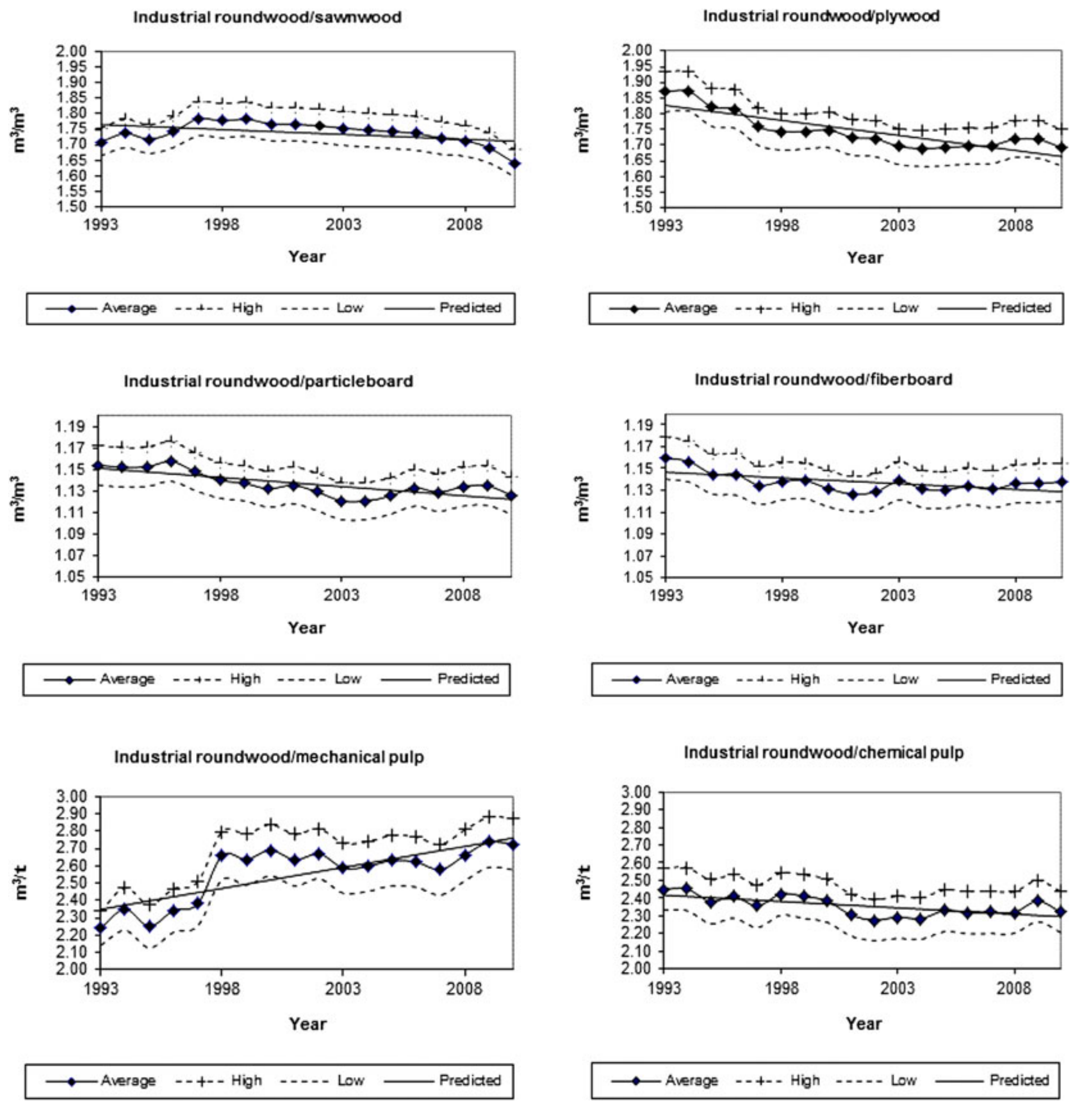

Figure 1. Industrial roundwood input per unit of sawnwood, wood-based panels, and wood pulp production, from 1993 to 2010. The average is over 180 countries. High and low is the average plus or minus one standard error. Predicted values are from a linear regression over time.

For example, Figure 7 shows the historical and predicted input of waste paper per ton of newsprint in four countries. In the base year, 2010, Japan and China used about three times as much waste paper per ton of newsprint as the USA and about twice as much as France. Starting from these initial conditions, the I–O coefficients of the four countries were assumed to change from 2010 to 2030 at the same rate of 0.003 t/t/year revealed by the average global trend from 1993 to 2010 (Table 2).

Future manufacturing costs in different countries were projected in similar fashion. For example, the manufacturing cost of newsprint in 2010 was three times as high in Japan as in France and in the USA and 50% higher than in China (Figure 8). The manufacturing cost was then projected to decrease from 2010 to 2030 at the same global rate of $1.8/t/year derived above (Table 3).

The projections with these average rates of technical were then compared with projections without technical change (i.e. with the I–O coefficients and manufacturing costs of 2010) to get a measure of the effects of technical change up to 2030. For sensitivity analysis, the projections were repeated with low or high rates of technical change, defined as the average yearly rates in Tables 2 and 3 plus or minus one standard error, corresponding to a 70% CI.

Effects of future technical change on the forest sector, 2010–2030

The GFPM was used with these future I–O coefficients and manufacturing costs, to project international production, consumption, prices, and net trade of the various products in different countries, and the evolution of the value added in industries and of the carbon stored in forests from 2010 to 2030. Except for the I–O

Table 2. Average yearly change of input per unit of output, from 1993 to 2010.

Input	Output	Yearly change	Unit	SE	t	$P > \|t\|$
Industrial roundwood	Sawnwood	−0.003	m^3/m^3/year	0.0015	−2.1	0.051*
	Veneer and plywood	−0.010		0.0014	−6.6	0.000***
	Particleboard	−0.002		0.0003	−5.1	0.000***
	Fiberboard	−0.001		0.0003	−3.2	0.005***
	Mechanical pulp	0.024	m^3/t/year	0.0046	5.2	0.000***
	Chemical pulp	−0.007		0.0020	−3.6	0.002***
Mechanical pulp		0.000	t/t/year	0.0003	−1.2	0.235
Chemical pulp		−0.003		0.0005	−6.3	0.000***
Other fiber pulp	Newsprint	0.000		0.0007	0.2	0.819
Waste paper		0.003		0.0004	6.4	0.000***
Mechanical pulp		−0.001	t/t/year	0.0003	−3.8	0.002***
Chemical pulp		−0.002		0.0006	−2.6	0.019**
Other fiber pulp	Printing and writing paper	0.000		0.0003	1.5	0.158
Waste paper		0.001		0.0007	2.1	0.052
Mechanical pulp		−0.001	t/t/year	0.0003	−2.9	0.010**
Chemical pulp		−0.001		0.0003	−2.8	0.012**
Other fiber pulp	Other paper and paperboard	0.000		0.0004	−1.0	0.334
Waste paper		0.002		0.0004	3.6	0.002***

*,**,***Significantly different from 0 at the 10%, 5%, and 1% level.

coefficients and manufacturing costs, and for the updated base year data, the parameters, such as the demand and supply elasticities and the forest area and stock growth equations, were the same as those used in the USDA Forest Service Outlook for World Forests and Forest Industries (Buongiorno et al. 2012). The following results present the differences in 2030 between the projections without technical change and the projections with average, high, or low technical change, other things being equal.

Price effects

In the calibration procedure and in the projections, all prices were expressed in constant US$ of 2010. With

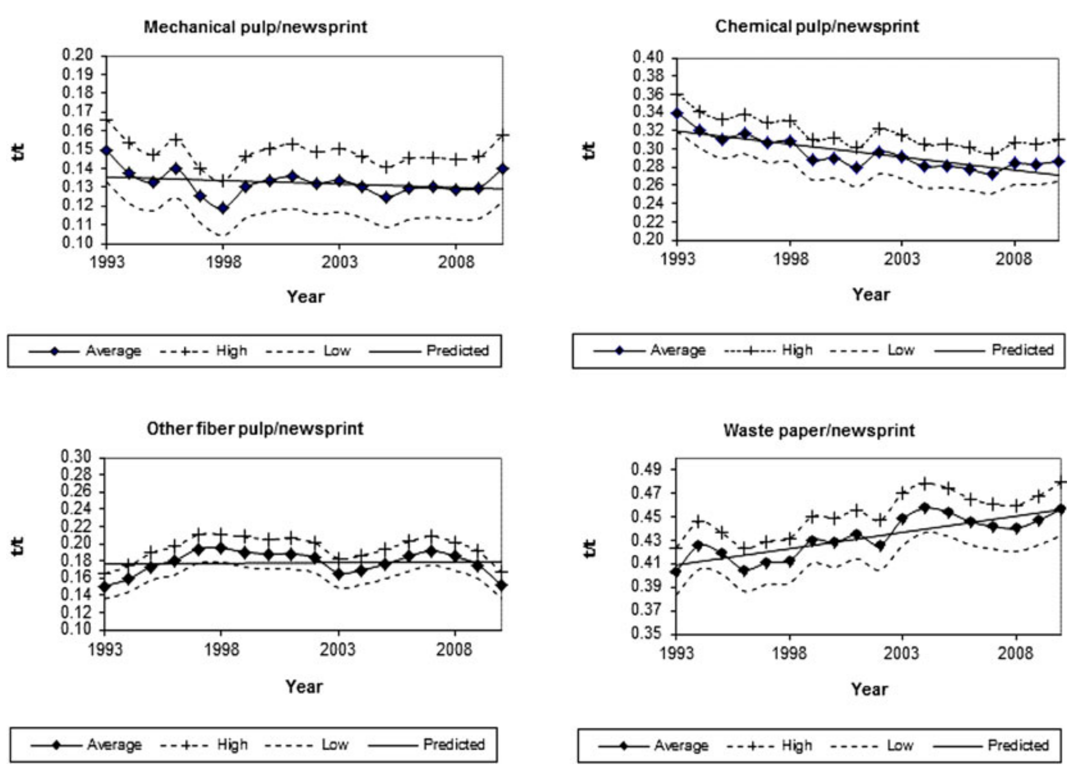

Figure 2. Fiber input per ton of newsprint production from 1993 to 2010. The average is over 180 countries. High and low is the average plus or minus one standard error. Predicted values are from a linear regression over time.

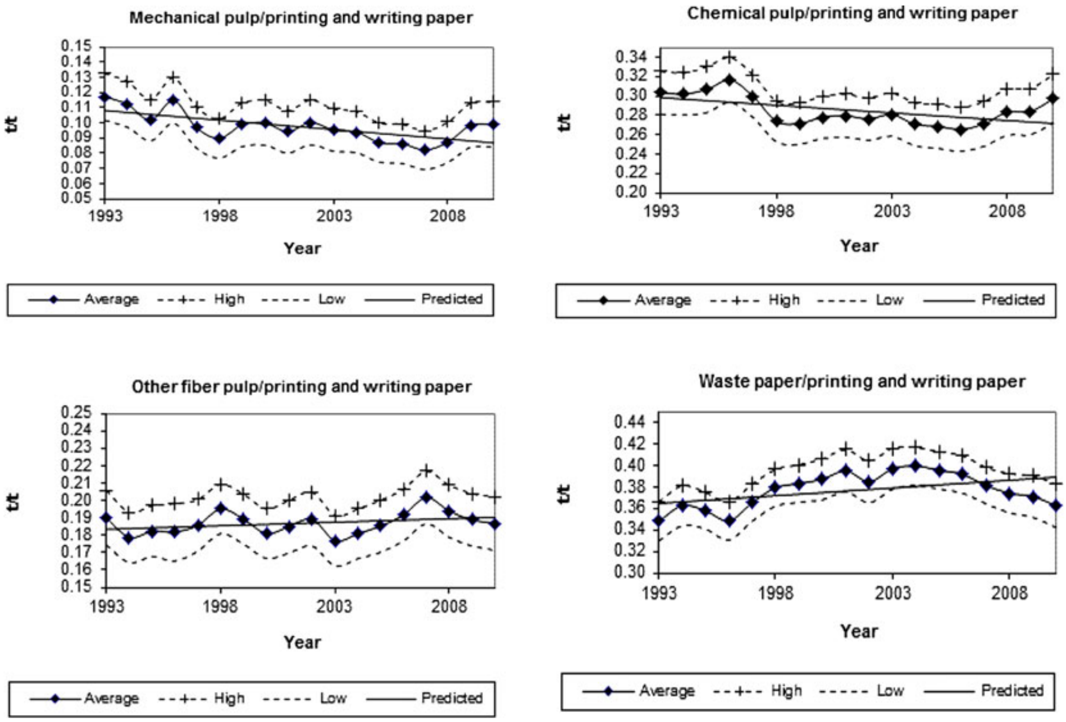

Figure 3. Fiber input per ton of printing and writing paper production from 1993 to 2010. The average is over 180 countries. High and low is the average plus or minus one standard error. Predicted values are from a linear regression over time.

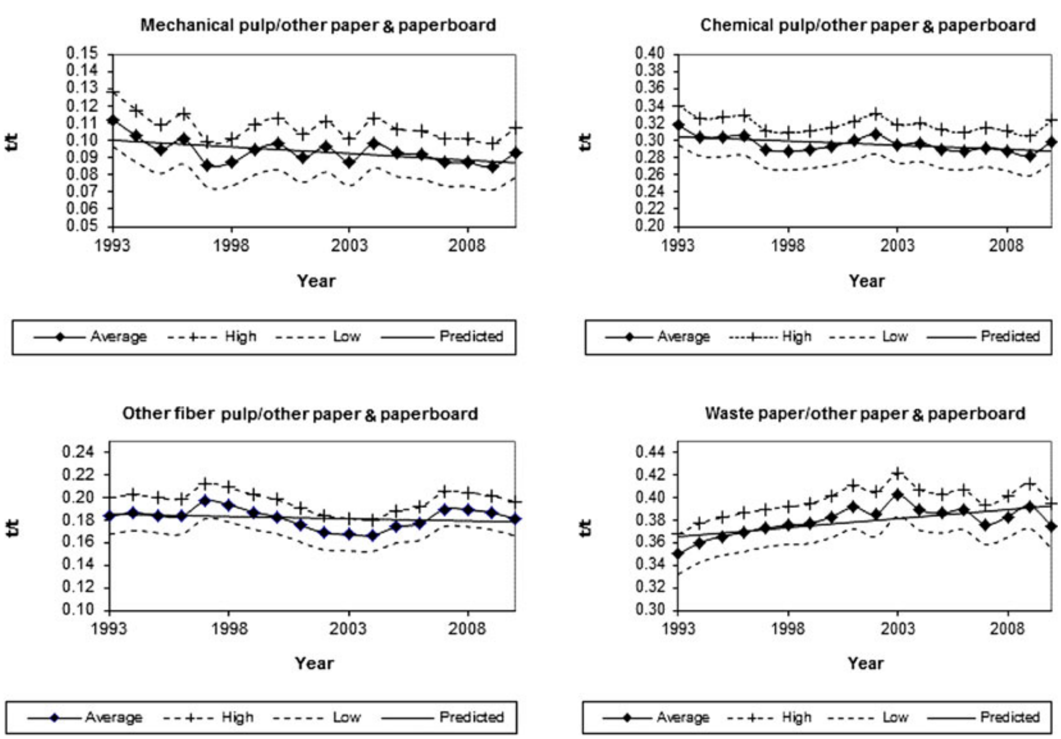

Figure 4. Fiber input per ton of other paper and paperboard production from 1993 to 2010. The average is over 180 countries. High and low is the average plus or minus one standard error. Predicted values are from a linear regression over time.

technical change, the price of industrial roundwood in 2030 was 6–8% lower depending on the scenario than without technical change (Table 4). This was due to the lower demand for industrial roundwood concurrent with the amount of roundwood needed per unit of product. As the amount of sawnwood per unit of industrial roundwood was stable, and there was little increase in the manufacturing cost of sawnwood, the price of sawnwood

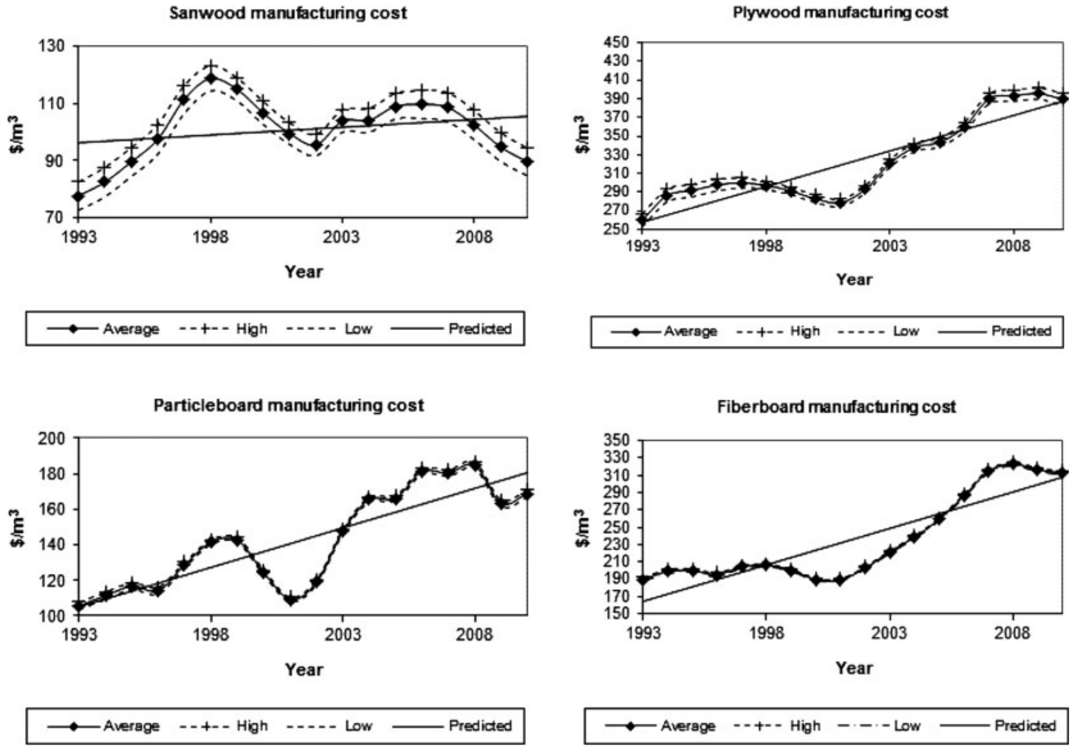

Figure 5. Manufacturing cost of sawnwood and wood-based panels, except wood cost, from 1993 to 2010. The average is over 180 countries. High and low is the average plus or minus one standard error. Predicted values are from a linear regression over time.

tended to be lower in the average and low scenario in accord with the price of industrial roundwood. The price of fuelwood decreased only slightly, due to the increase in growing stock induced by the lower demand for industrial roundwood. The prices of wood-based panels, wood pulp, waste paper, and other paper and paperboard were substantially higher with technical change, in all three scenarios, due to the positive trends of manufacturing cost observed above. However, the price of newsprint and printing and writing paper, and other fiber pulp was lower in 2030 with the low technical change scenario.

Effects on industrial roundwood

Table 5 shows the percent differences of industrial roundwood production and consumption in 2030 due to the three projected rates of technical change, in world regions and major countries. At the world level, industrial roundwood consumption was 5–7% lower, or 116 million m^3 lower on average, with technical change than without it. The drop in consumption was 3–5 times as large in percent in developing as in developed countries, stemming mostly from 14% to 15% lower consumption in Asia due in part to a 23–24% lower consumption in China. Industrial roundwood consumption was also lower (7–15%) in the USA, but it was practically unaffected in EU-27 countries. The impact of technical change on industrial roundwood production was more evenly distributed across countries, in relative terms, than that of consumption, with a decrease of 6–8% in developed countries and of 4–6% in developing. Concurrently, the

Table 3. Average yearly change in manufacturing cost, except wood and fiber cost, from 1993 to 2010.

	Yearly change	Unit	SE	t	$P > \|t\|$
Sawnwood	0.5		0.5	1.1	0.296
Veneer and plywood	7.6	\$/m^3/year	0.9	8.3	0.000***
Particleboard	4.4		0.7	6.7	0.000***
Fiberboard	8.4		1.1	7.4	0.000***
Mechanical pulp	6.3		0.9	7.0	0.000***
Chemical pulp	7.1	\$/t/year	1.4	5.2	0.000***
Newsprint	−1.8		0.9	−2.0	0.068*
Printing and writing paper	−3.0		1.2	−2.4	0.030**
Other paper and paperboard	4.1		1.6	2.6	0.020**

*,**,*** Significantly different from 0 at the 10%, 5%, and 1% level.

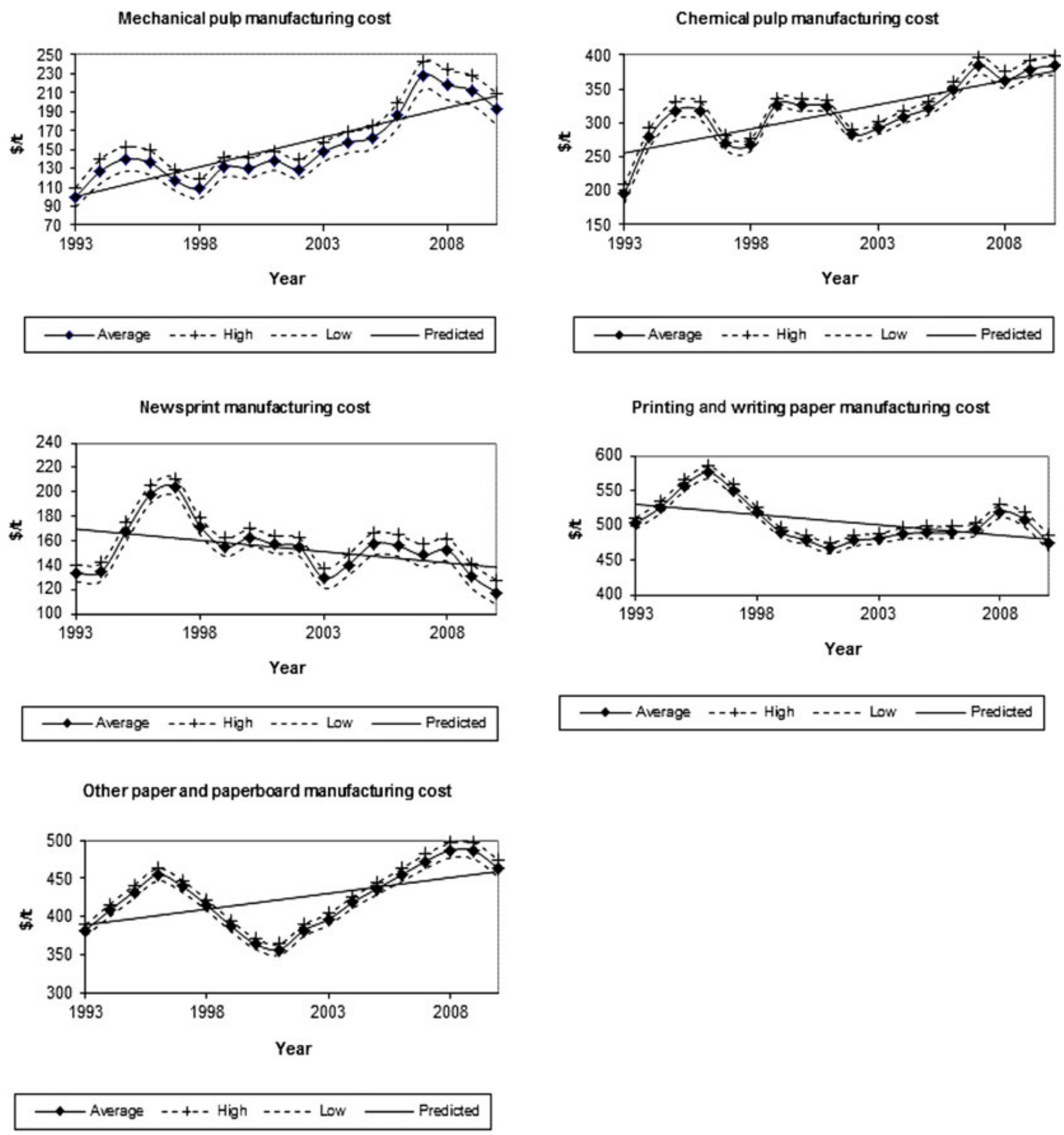

Figure 6. Manufacturing cost of wood pulp and paper and paperboard, except wood and fiber cost, from 1993 to 2010. The average is over 180 countries. High and low is the average plus or minus one standard error. Predicted values are from a linear regression over time.

trade balance of industrial roundwood improved due to technical change for developing countries and worsened for developed countries.

Effects on wood pulp

As noted earlier, an important technical change in the forest sector is the more efficient use of wood fiber and its substitution by recycled waste paper and other fiber pulp. Table 6 shows the differences in production and consumption of wood pulp due to technical change in 2030 in world regions and selected countries. Globally, the consumption of wood pulp (mechanical and chemical) was 17–19% lower, or 39 million metric tons lower on average, in 2030 with technical change than without it (Table 6). The relative decrease of consumption was 2–3 times higher in developed countries than in developing. The relative decrease of consumption was especially high in the USA (−21 to −25%) and in the EU-27 (−21%). It was substantially less in other large countries like Brazil, China, and India. Production dropped even more than consumption in relative terms in the USA, leading to a worsening of its trade balance by some 7 million tons in 2030 under the average scenario. In the EU-27 instead, production dropped less than consumption, and the trade balance improved by about 6 million tons in 2030 with the average technical change scenario.

Effects on waste paper utilization and recovery

While wood pulp consumption was lower in 2030 due to technical change, waste paper consumption was higher (Table 7). The world waste paper consumption and production were 8–9%, or 27 million tons on

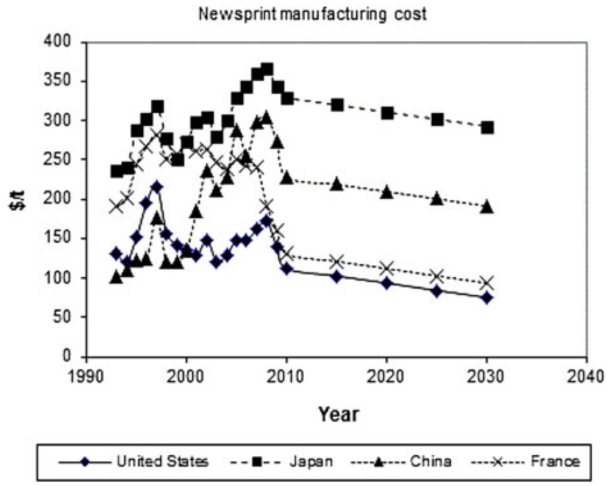

Figure 7. Newsprint manufacturing cost, except fiber cost, estimated from 1993 to 2010 and projected from 2010 to 2030 in selected countries.

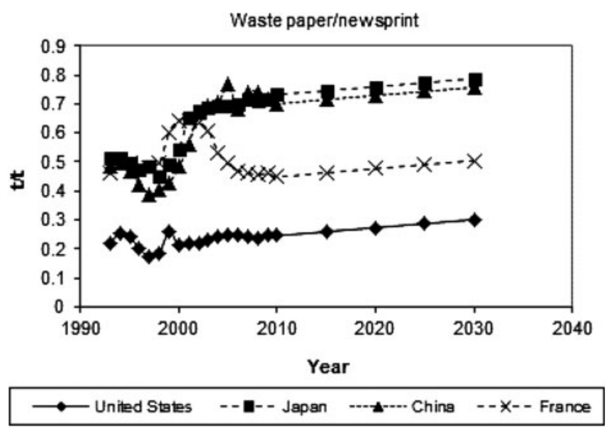

Figure 8. Input of waste paper per unit of newsprint production, estimated from 1993 to 2010 and projected from 2010 to 2030.

Table 4. Percent difference in world prices in 2030 relative to the base scenario without technical change.

		Rate of technical change		
Commodity	Base scenario price[a] ($/m^3)	Low (%)	Average (%)	High (%)
Fuelwood	57	−1	−1	−1
Industrial roundwood	102	−8	−7	−6
Sawnwood	254	−10	−4	2
Veneer and plywood	560	17	21	26
Particleboard	286	21	27	32
Fiberboard	427	31	37	42
	$/t			
Mechanical pulp	478	25	32	39
Chemical pulp	615	12	18	23
Other fiber pulp	1269	−3	7	18
Waste paper	170	14	17	18
Newsprint	627	−7	3	14
Printing and writing paper	976	−8	−1	6
Other paper and paperboard	957	7	14	21

[a]US$ of 2010.

Table 5. Percent difference in industrial roundwood consumption and production in 2030 due to technical change, relative to the base scenario without technical change.

	Consumption				Production			
		Rate of technical change[a]				Rate of technical change[a]		
	Base scenario (10^6 m^3)	Low (%)	Average (%)	High (%)	Base scenario (10^6 m^3)	Low (%)	Average (%)	High (%)
Africa	57	6	5	5	70	−6	−5	−4
Egypt	0.4	23	17	11	0.2	−3	−3	−2
Nigeria	9	−2	−2	−1	9	−2	−2	−1
South Africa	15	21	19	16	24	−9	−7	−6
North/Central America	474	−10	−9	−6	483	−6	−6	−5
Canada	184	−1	−2	−4	184	−8	−7	−6
Mexico	4	−11	−10	−8	4	−10	−9	−7
USA	281	−15	−13	−7	289	−5	−5	−4
South America	198	−1	0	1	201	−7	−6	−5
Argentina	11	−4	−5	−5	11	−4	−5	−5
Brazil	130	−6	−5	−4	133	−7	−6	−5
Chile	40	19	19	20	38	−5	−5	−4
Asia	498	−15	−15	−14	359	−6	−5	−4
China	268	−24	−23	−23	153	−3	−2	−2
India	38	−9	−7	−5	22	−16	−12	−9
Indonesia	59	−1	0	1	62	−6	−5	−4
Japan	39	23	23	20	23	−9	−8	−6
Republic of Korea	14	−32	−31	−29	6	−9	−8	−6
Malaysia	20	−37	−35	−33	24	−10	−9	−7
Oceania	36	−19	−15	−11	73	−9	−8	−7
Australia	14	−10	−4	4	37	−11	−9	−8
New Zealand	19	−28	−26	−24	31	−8	−7	−5
Europe	561	−1	0	0	623	−9	−8	−7
EU-27	423	1	1	0	428	−8	−8	−7
Austria	27	−36	−34	−32	12	−8	−7	−6
Finland	52	32	32	22	49	−7	−6	−5
France	25	−29	−23	−16	34	−10	−9	−7
Germany	73	−11	−9	−8	72	−11	−9	−8
Italy	9	−13	−14	−14	3	−7	−6	−5
Russian Federation	102	−4	2	8	145	−10	−8	−7
Spain	15	−7	−7	−6	15	−8	−7	−6
Sweden	85	17	13	10	82	−7	−6	−5
UK	11	−9	−8	−7	11	−9	−8	−7
Developed	1115	−4	−3	−2	1212	−8	−7	−6
Developing	709	−12	−12	−11	597	−6	−5	−4
World	1824[b]	−7	−6	−5	1808	−7	−6	−5

[a]Average = yearly change in Tables 2 and 3; low and high = average plus or minus one standard error.
[b]Differs from production due to unbalanced trade in base year kept constant in the projections.

average, higher in 2030 with technical change than without it. This was 12 million tons less than the decrease in world wood pulp consumption. Thus, the substitution of waste paper for wood pulp accounted for 69% of the decrease in the use of wood pulp in the manufacture of other paper and paperboard. The rest was due to better utilization of mechanical and chemical wood pulp and to increasing use of other fiber pulp (straw, bagasse, etc.). The increase in waste paper consumption was especially high in the EU-27 and in many individual countries production (i.e. waste paper recovered) also increased accordingly. But, in the USA, although production was 3–6% higher with technical change, depending on the scenario, consumption was 7–9% lower, reflecting a lack of competitiveness of the US pulp and paper industry during the projected period.

Consequences for value added and carbon storage

In this study, value added was defined as the value of the products minus the value of wood and fiber used in

Table 6. Percent difference in wood pulp consumption and production in 2030 due to technical change, relative to the base scenario without technical change.

	Consumption				Production			
		Rate of technical change[a]				Rate of technical change[a]		
	Base scenario (10^3 t)	Low (%)	Average (%)	High (%)	Base scenario (10^3 t)	Low (%)	Average (%)	High (%)
Africa	2922	−3	−9	−15	2789	13	8	3
Egypt	299	4	3	1	55	52	40	27
Nigeria	50	−29	−30	−35	0			
South Africa	1975	0	−7	−13	2177	20	15	9
North/Central America	65,821	−24	−27	−27	92,213	−30	−29	−27
Canada	11,299	−43	−43	−43	24,383	−27	−28	−28
Mexico	1299	−2	8	7	198	−30	−28	−26
USA	53,074	−21	−25	−24	67,510	−30	−29	−26
South America	11,815	−9	−7	−8	20,055	9	9	9
Argentina	1031	2	−1	−3	1068	2	−1	−3
Brazil	8481	−9	−8	−10	12,552	0	0	1
Chile	1253	−22	−12	−2	5469	38	37	36
Asia	67,626	−12	−9	−7	35,293	−19	−16	−15
China	35,499	−16	−14	−10	10,798	−35	−33	−30
India	4723	−14	−10	−6	3055	−22	−15	−9
Indonesia	6362	11	14	11	7175	7	8	7
Japan	11,104	−16	−13	−12	10,535	−16	−14	−15
Republic of Korea	3917	−14	−14	−22	1128	−39	−36	−36
Malaysia	364	−17	4	13	210	−42	−38	−33
Oceania	2885	−27	−12	0	4013	−40	−33	−23
Australia	2032	−25	−4	15	1821	−33	−23	−9
New Zealand	822	−31	−33	−35	2161	−45	−40	−35
Europe	63,216	−22	−21	−19	62,333	−11	−12	−11
EU-27	53,009	−21	−21	−21	49,879	−10	−11	−12
Austria	3771	−14	−12	−10	2633	−30	−27	−24
Finland	9855	−20	−29	−37	12,287	5	−1	−7
France	3515	−2	−5	−6	2348	−37	−35	−31
Germany	8050	−12	−7	−3	4438	−35	−31	−27
Italy	4169	−9	−9	−12	511	−58	−54	−52
Russian Federation	7233	−22	−11	6	9129	−9	−8	−4
Spain	2143	−11	−9	−8	2102	−11	−9	−10
Sweden	10,939	−52	−47	−40	14,982	−13	−9	−4
UK	1499	0	7	5	325	−18	−6	−9
Developed	143,731	−22	−23	−22	170,922	−22	−21	−20
Developing	70,553	−11	−8	−7	45,774	−7	−6	−4
World	214,284[b]	−19	−18	−17	216,695	−19	−18	−17

[a]Average = yearly change in Tables 2 and 3; low and high = average plus or minus one standard error.
[b]Differs from production due to unbalanced trade in base year kept constant in the projections.

making them. Table 8 shows the differences of value added in 2030, due to technical change, by scenario. At world level, value added was 8–20%, or \$49 10^9 to \$116 10^9, higher with technical change than without it. The largest part of this difference was in developing countries, mainly in China where value added was \$19 10^9 to \$41 10^9 higher in 2030 depending on the scenario. There was also a large increase of value added in the EU-27 countries (10–19% or \$12 10^9 to \$23 10^9), but only a small change in the USA.

As technical change lowered the wood consumption (Table 5), it had a positive effect on forest growing stock and thus on carbon sequestration in forests. Other things being equal, technical change from 2010 to 2030 led to a level of CO_2e stored in world forests that was approximately 0.2%, or 2–2.6 10^9 t, higher in 2030 (Table 9). Of this total difference in carbon sequestration, 70% was in developed countries, especially in Europe and in North America. There was less accumulation of CO_2e in Asia and South America, and hardly any in Africa.

Table 7. Percent difference in waste paper consumption and production in 2030 due to technical change, relative to the base scenario without technical change.

	Consumption				Production			
		Rate of technical change[a]				Rate of technical change[a]		
	Base scenario (10^3 t)	Low (%)	Average (%)	High (%)	10^3 t	Low (%)	Average (%)	High (%)
Africa	2429	17	13	6	2630	15	12	6
Egypt	473	22	20	16	471	20	18	16
Nigeria	5	21	23	19	12	8	8	9
South Africa	1423	17	9	1	1539	15	9	1
North/Central America	40,090	−5	−6	−5	68,306	7	6	5
Canada	3167	−32	−31	−30	4398	14	17	15
Mexico	5410	20	28	22	4280	12	14	15
USA	31,126	−7	−9	−8	58,927	6	4	3
South America	9320	6	8	7	9100	6	8	7
Argentina	675	18	15	11	661	18	15	11
Brazil	6015	5	6	4	6013	5	6	4
Chile	780	−11	2	16	746	−10	2	16
Asia	181,598	9	10	10	149,004	10	11	12
China	125,234	6	7	8	94,515	12	14	15
India	6055	20	20	21	2929	12	14	15
Indonesia	8550	37	37	31	6714	12	14	15
Japan	18,449	4	4	2	22,981	2	0	−1
Republic of Korea	10,549	12	6	−12	8683	1	0	−2
Malaysia	1947	12	32	36	1870	11	14	15
Oceania	2248	−10	14	33	3962	2	1	0
Australia	2199	−11	13	33	3591	1	−1	−2
New Zealand	22	73	93	110	341	14	17	18
Europe	60,514	14	16	16	65,853	6	8	8
EU-27	54,687	15	16	15	59,215	7	7	7
Austria	4771	9	8	8	1862	3	1	0
Finland	860	35	31	28	1050	16	15	13
France	4181	24	18	14	6540	14	17	18
Germany	21,568	20	18	17	17,092	0	−1	−3
Italy	4248	9	8	5	5467	14	17	18
Russian Federation	2723	−10	9	37	3174	−3	12	21
Spain	4420	18	17	15	4093	12	14	15
Sweden	2518	−42	−25	−6	1763	−15	−3	−1
UK	4662	33	35	27	9405	1	−1	−2
Developed	117,561	5	6	6	158,397	6	5	5
Developing	178,638	10	11	11	140,458	11	13	14
World	296,199[b]	8	9	9	298,855	8	9	9

[a]Average = yearly change in Tables 2 and 3; low and high = average plus or minus one standard error.
[b]Differs from production due to unbalanced trade in base year kept constant in the projections.

Summary and discussion

This paper dealt with the representation of technical change for forest sector models in which some or all of the demand and supply relationships are represented by activity analysis. In this context, technical change is reflected in changes of the I–O coefficients and of the attendant manufacturing costs. The GFPM was used as an example, although the methods should be useful for other models that use a similar representation of technologies.

The method recognizes that although many data are available about the forest sector, many are not. In particular, few data exist on I–O coefficients and manufacturing costs. Furthermore, even the available data are subject to error. The goal-programming approach described above allows estimates of the I–O coefficients and manufacturing cost that are consistent with the data on production and trade (quantity and value) available at international level through the FAOSTAT (FAO 2013).

Table 8. Difference in value added in 2030 due to technical change, relative to the base scenario without technical change.

		Difference with rate of technical change[a]					
		Low		Average		High	
	Base scenario (10^6 \$[b])	10^6 \$	%	10^6 \$	%	10^6 \$	%
Africa	3118	1358	44	1511	48	1589	51
Egypt	718	149	21	172	24	186	26
Nigeria	−245	30	−12	49	−20	69	−28
South Africa	2149	742	35	755	35	702	33
North/Central America	119,416	−2409	−2	3914	3	11,213	9
Canada	20,566	−984	−5	160	1	1308	6
Mexico	5329	1057	20	1786	34	1969	37
USA	92,354	−2634	−3	1736	2	7629	8
South America	22,839	5152	23	7128	31	8723	38
Argentina	1546	343	22	406	26	456	30
Brazil	14,876	2472	17	3787	25	4789	32
Chile	2877	1863	65	2192	76	2540	88
Asia	302,751	32,501	11	49,347	16	65,484	22
China	202,285	18,947	9	29,158	14	41,345	20
India	17,854	2128	12	3178	18	4219	24
Indonesia	13,031	4599	35	5501	42	5923	45
Japan	27,012	1963	7	3230	12	4089	15
Republic of Korea	12,489	678	5	775	6	222	2
Malaysia	5914	−42	−1	702	12	1096	19
Oceania	6722	−822	−12	107	2	1210	18
Australia	4263	−108	−3	659	15	1561	37
New Zealand	2197	−821	−37	−673	−31	−487	−22
Europe	141,345	13,643	10	21,226	15	28,255	20
EU-27	122,576	11,880	10	17,778	15	22,940	19
Austria	9311	−293	−3	119	1	538	6
Finland	11,420	1405	12	1097	10	634	6
France	10,535	813	8	1270	12	1905	18
Germany	35,106	4499	13	6101	17	7782	22
Italy	8732	760	9	1115	13	1387	16
Russian Federation	9874	1738	18	2879	29	4330	44
Spain	6907	1096	16	1509	22	1854	27
Sweden	10,834	−1031	−10	−253	−2	716	7
UK	6153	1522	25	1931	31	1967	32
Developed	291,185	12,017	4	27,373	9	43,418	15
Developing	305,007	37,406	12	55,860	18	73,056	24
World	596,191	49,423	8	83,232	14	116,474	20

[a]Average = yearly change in Tables 2 and 3; low and high = average plus or minus one standard error.
[b]In constant US\$ of 2010.

Concurrently, the method adjusts, if needed, the data on production, in accord with their value, in cases where they disagree with prior engineering knowledge: the limits on the amount of wood needed to make wood products, and the limits on the amounts of wood or other fiber pulp needed in making paper and paperboard. In the current procedure, import and export data are assumed to be correct. The model formulation could be readily modified to allow for errors in import and export data as well. However, the additional variables would increase the possibility of multiple solutions and instability of the resulting I–O coefficients with small variations of the data. The assumption of perfect competition underlying the estimation of manufacturing costs also warrants further attention and could be lifted if enough international cost data on forest industries became available.

The estimation of manufacturing costs requires further assumptions: that the unit values of world imports and exports give a good indication of prices, and that the prices reflect a global equilibrium with only a normal return to capital (zero profit). These are clearly heroic assumptions. However, they agree with general equilibrium principles, and the results are such that the solution of the model (maximization of social surplus) exactly replicates the input data (after eventual adjustments described

Table 9. Difference in CO_2e stored in forest biomass in 2030 due to technical change, relative to the base scenario without technical change.

		Difference with rate of technical change[a]					
		Low		Average		High	
	Base scenario (10^6 t)	10^6 t	%	10^6 t	%	10^6 t	%
Africa	185,486	76	0.0	67	0.0	56	0.0
Egypt	13	0	0.0	0	0.0	0	0.0
Nigeria	1741	4	0.2	4	0.2	3	0.2
South Africa	1822	39	2.1	34	1.9	28	1.5
North/Central America	220,832	597	0.3	541	0.2	461	0.2
Canada	88,650	268	0.3	246	0.3	211	0.2
Mexico	4377	9	0.2	8	0.2	7	0.2
USA	120,150	312	0.3	281	0.2	238	0.2
South America	363,744	269	0.1	246	0.1	217	0.1
Argentina	5503	10	0.2	11	0.2	10	0.2
Brazil	245,136	179	0.1	162	0.1	141	0.1
Chile	6495	47	0.7	44	0.7	40	0.6
Asia	112,449	434	0.4	380	0.3	319	0.3
China	33,036	92	0.3	83	0.3	72	0.2
India	6963	58	0.8	45	0.6	31	0.4
Indonesia	24,597	80	0.3	71	0.3	62	0.3
Japan	6115	38	0.6	34	0.6	29	0.5
Republic of Korea	2429	7	0.3	7	0.3	5	0.2
Malaysia	10,008	45	0.5	41	0.4	34	0.3
Oceania	41,340	124	0.3	111	0.3	94	0.2
Australia	25,185	68	0.3	61	0.2	52	0.2
New Zealand	8040	45	0.6	40	0.5	34	0.4
Europe	258,264	1076	0.4	987	0.4	857	0.3
EU-27	63,020	719	1.1	665	1.1	584	0.9
Austria	2064	22	1.1	20	1.0	17	0.8
Finland	4850	79	1.6	73	1.5	62	1.3
France	5927	70	1.2	63	1.1	53	0.9
Germany	11,539	131	1.1	115	1.0	97	0.8
Italy	4236	4	0.1	3	0.1	3	0.1
Russian Federation	171,290	265	0.2	238	0.1	202	0.1
Spain	2351	23	1.0	21	0.9	18	0.8
Sweden	8275	124	1.5	114	1.4	97	1.2
UK	993	21	2.1	19	1.9	16	1.6
Developed	511,339	1848	0.4	1684	0.3	1450	0.3
Developing	670,776	728	0.1	649	0.1	554	0.1
World	1182,115	2576	0.2	2333	0.2	2004	0.2

[a]Average = yearly change in Tables 2 and 3; low and high = average plus or minus one standard error.

above). This is a necessary condition of model validation, even though it is clearly not sufficient. Another limitation of this study is that changes in manufacturing costs are not due solely to technical change, but also to changes in the cost of labor, energy, and capital. Further work is needed to decompose the manufacturing cost into those components, and then obtain the technical change effect as a residual. A difficulty in that respect is the lack of international statistics on the cost of the various inputs in forest industries.

This study has dealt only with technological change in the I–O part of forest sector models like the GFPM. Technical change affects other parts, including demand (where changes of techniques in end products utilization are represented in the GFPM by time trends), transportation costs, and wood supply, which should be analyzed further in future studies. Meanwhile, with the definitions used here, the results of the model simulation with and without technical change suggest that technical change has important effects on prices, production and consumption, resources utilization, and carbon storage. How can we then improve the representation of technical change in future studies? Although there was no evidence of convergence of technologies across countries, it is possible that this result be influenced by the bounds on the estimated I–O coefficients, although as shown in the appendix a wide range of coefficients was allowed. Still, this issue deserves further study given past mixed results concerning macro-economic convergence (Barro and Sala-i-Martin 1992; Romer 1994; Prichett 1997; Sala-i-Martin 2006). Another research direction is to make technical change endogenous. A most elegant option would be a full nonlinear model whereby I–O coefficients are functions of the endogenous production variables. An early proposal along those lines is in Lahiri (1976), but it remains a theoretical concept with few if any application. A more feasible approach is to allow for several technologies in making a particular product. This option was used in early applications of the GFPM structure to the North American pulp and paper industry. A similar approach could be used, in principle, to introduce new, not yet marketed, technologies. To what extent this is feasible for global models of the entire forest sector, and how much it would improve with respect to exogenous technical change is a good possible subject for further study.

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Appendix

This example deals with the estimation of the I–O coefficients and manufacturing costs for China for the year 2011.

Data:

In Table A1, *r*, *e*, and *i* refer to raw material, end product, and intermediate product, respectively. Production, import, and export are averages of FAOSTAT statistics for 2010, 2011, and 2012. Prices are FAOSTAT unit values of world exports plus transport cost and import tariffs. Weights are user defined, here they are set proportional to the prices, in addition the weight of differences in production compared to differences in I–O quantities is set at $\beta = 0.90$.

All bounds are user defined. In addition to the bounds in Table A2, the upper bound on the post-consumption recovery rate of products 91, 92, and 93 is 0.80 and the lower bound is 0. The upper bound on the manufacturing cost is 9999 and the lower bound is 1.

Goal-programming formulation:

$$\begin{aligned}\min\, & 0.90 \times 1.2Y_{81}^{+} + 0.90 \times 1.2Y_{81}^{-} + \ldots \\ & + 0.90 \times 10.6Y_{93}^{+} + 0.90 \times 10.6Y_{93}^{-} \\ & + 0.10(1.2 \times 2.8)^{1/2} Y_{81,83}^{+} \\ & + 0.10(1.2 \times 2.8)^{1/2} Y_{81,83}^{-} + \ldots \\ & + 0.10(2.2 \times 10.6)^{1/2} Y_{90,93}^{+} \\ & + 0.10(2.2 \times 10.6)^{1/2} Y_{90,93}^{-}\end{aligned}$$

Subject to:
Non negativity:

$$\begin{aligned}& Y_{81}, \ldots, Y_{93}, Y_{81}^{+}, Y_{81}^{-}, \ldots, Y_{93}^{+}, Y_{93}^{-}, Y_{81,83}, \ldots, \\ & Y_{90,93}, Y_{81,83}^{+}, Y_{81,83}^{-}, \ldots, Y_{90,93}^{+}, Y_{90,93}^{-} \geq 0\end{aligned}$$

Deviation of estimated from reported production:

$$\begin{aligned}& Y_{81} + Y_{81}^{-} - Y_{81}^{+} = 105373 \\ & \ldots \\ & Y_{93} + Y_{93}^{-} - Y_{93}^{+} = 73302\end{aligned}$$

Deviation of estimated from expected input:

$$\begin{aligned}& Y_{81,83} - \frac{1.05 + 3.00}{2} Y_{83} + Y_{81,83}^{-} - Y_{81,83}^{+} = 0 \\ & \ldots \\ & Y_{90,93} - \frac{0.00 + 1.10}{2} Y_{93} + Y_{90,93}^{-} - Y_{90,93}^{+} = 0\end{aligned}$$

Material balance for raw materials and intermediate products:

$$\begin{aligned}& Y_{81} - Y_{81,83} - Y_{81,84} - Y_{81,85} - Y_{81,86} - Y_{81,87} - Y_{81,88} \\ & \quad = 232 - 54729 \\ & \quad \ldots \\ & Y_{90} - Y_{90,91} - Y_{90,92} - Y_{90,93} = 1314 - 28078\end{aligned}$$

Material balance for end products:

$$\begin{aligned}& Y_{83} \geq 748 - 21037 \\ & \ldots \\ & Y_{93} \geq 2502 - 2959\end{aligned}$$

Upper bound on input per output:

$$\begin{aligned}& Y_{81,83} - 3.00Y_{83} \leq 0 \\ & \ldots \\ & Y_{90,93} - 1.10Y_{93} \leq 0\end{aligned}$$

Lower bound on input per output:

$$\begin{aligned}& Y_{81,83} - 1.05Y_{83} \geq 0 \\ & \ldots \\ & Y_{90,93} - 0.00Y_{93} \geq 0\end{aligned}$$

Upper bound on total inputs per output:

$$\begin{aligned}& Y_{87,91} + Y_{88,91} + Y_{89,91} + Y_{90,91} - 1.10Y_{91} \leq 0 \\ & Y_{87,92} + Y_{88,92} + Y_{89,92} + Y_{90,92} - 1.10Y_{92} \leq 0 \\ & Y_{87,93} + Y_{88,93} + Y_{89,93} + Y_{90,93} - 1.10Y_{93} \leq 0\end{aligned}$$

Lower bound on total inputs per output:

$$\begin{aligned}& Y_{87,91} + Y_{88,91} + Y_{89,91} + Y_{90,91} - 1.00Y_{91} \geq 0 \\ & Y_{87,92} + Y_{88,92} + Y_{89,92} + Y_{90,92} - 0.85Y_{92} \geq 0 \\ & Y_{87,93} + Y_{88,93} + Y_{89,93} + Y_{90,93} - 0.85Y_{93} \geq 0\end{aligned}$$

Upper bound on post-consumer recovery:

$$\begin{aligned}& Y_{90} - 0.80Y_{91} - 0.80Y_{92} - 0.80Y_{93} \leq 0.80(627 - 47) \\ & \quad + 0.80(1561 - 2889) + 0.80(2959 - 2502)\end{aligned}$$

Lower bound on post-consumer recovery:

$$\begin{aligned}& Y_{90} - 0.0Y_{91} - 0.0Y_{92} - 0.0Y_{93} \geq 0.00(627 - 47) \\ & \quad + 0.00(1561 - 2889) + 0.00(2959 - 2502)\end{aligned}$$

Upper bound on manufacturing cost:

$$\begin{aligned}& 284.9Y_{83} - 121.2Y_{81,83} - 9999Y_{83} \leq 0 \\ & \ldots \\ & 1064.9Y_{93} - 554.8Y_{87,93} - 693.4Y_{88,93} - 1312.0Y_{89,93} \\ & \quad - 218.8Y_{90,93} - 9999Y_{93} \leq 0\end{aligned}$$

Lower bound on manufacturing cost:

$$\begin{aligned}& 284.9Y_{83} - 121.2Y_{81,83} - 1Y_{83} \geq 0 \\ & \ldots \\ & 1064.9Y_{93} - 554.8Y_{87,93} - 693.4Y_{88,93} - 1312.0Y_{89,93} \\ & \quad - 218.8Y_{90,93} - 1Y_{93} \geq 0\end{aligned}$$

Solution:

In the optimum solution, all the deviational variables, Y^{+} and Y^{-} equal zero, except $Y_{81}^{+} = 8369.6$. Thus, the estimated production is the same as the reported production, except for industrial roundwood for which the estimated production exceeds the reported by 7.9%.

At the optimum, the estimated non-zero inputs per outputs are:

$Y_{81,83}$	$Y_{81,84}$	$Y_{81,85}$	$Y_{81,86}$	$Y_{81,87}$	$Y_{81,88}$	$Y_{87,93}$	$Y_{88,93}$	$Y_{89,93}$	$Y_{90,91}$	$Y_{90,92}$	$Y_{90,93}$
48,162	50,110.2	12,185.7	47,109.6	1125	9547	909	20,766	12,031	4429.7	27,103	42,241.4

The corresponding estimated non-zero I–O coefficients are:

$$A_{81,83} = \frac{48162}{45869} = 1.05, \text{ and similarly,}$$

$$A_{81,84} = 1.05, A_{81,85} = 0.95, A_{81,86} = 0.95, A_{81,87} = 1.30, A_{81,88} = 1.30, A_{87,93} = 0.012,$$

$$A_{88,93} = 0.283, A_{89,93} = 0.164, A_{90,91} = 1.10, A_{90,92} = 1.10, A_{90,93} = 0.576$$

The estimated manufacturing costs are:

$$m_{83} = 284.9 - (1.05)121.2 = 157.6, \text{ and similarly,}$$

$$m_{84} = 445.7, m_{85} = 198.4, m_{86} = 317.9, m_{87} = 397.3, m_{88} = 535.8, m_{91} = 441.9, m_{92} = 733.3,$$

$$m_{93} = 1064.9 - 0.012 \times 554.8 - 0.283 \times 693.4 - 0.164 \times 1312 - 0.576 \times 218.8 = 520.2$$

Table A1. FAOSTAT statistics and weights.

Product		Type	Production (q) (1000 m^3)	Import (z) 1000 m^3	Export (x) 1000 m^3	Price (p) (\$/m^3)	Weight (w)
81	Industrial roundwood	*r*	105,373	54,729	232	121.2	1.2
83	Sawnwood	*e*	45,869	21,037	748	284.9	2.8
84	Veneer and plywood	*e*	47,724	2049	9228	573.0	5.7
85	Particleboard	*e*	12,827	820	188	313.5	3.1
86	Fiberboard	*e*	49,589	604	2868	433.0	4.3
			(1000 t)	(1000 t)	(1000 t)	($/t)	
87	Mechanical pulp	*i*	865	44	0	554.8	5.5
88	Chemical pulp	*i*	7344	13,461	39	693.4	6.9
89	Other fiber pulp	*r*	12,036	70	75	1312.0	13.1
90	Waste paper	*r*	47,010	28,078	1314	218.8	2.2
91	Newsprint	*e*	4027	627	47	682.6	6.8
92	Printing and writing paper	*e*	24,639	1561	2889	974.0	9.7
93	Other paper and paperboard	*e*	73,302	2959	2502	1064.9	10.6

Table A2. Upper and lower bounds on I–O coefficients.

Output	83	84	85	86	87	88	91	92	93
Input					Upper bound				
81	3.00	3.00	1.50	1.50	4.00	4.00			
87							1.10	1.10	1.10
88							1.10	1.10	1.10
89							1.10	1.10	1.10
90							1.10	1.10	1.10
Total							1.10	1.10	1.10
					Lower bound				
81	1.05	1.05	0.95	0.95	1.30	1.30			
87							0.00	0.00	0.00
88							0.00	0.00	0.00
89							0.00	0.00	0.00
90							0.00	0.00	0.00
Total							1.00	0.85	0.85