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ORIGINAL ARTICLE

Efficiency in wood and fiber utilization in OECD countries

Hiroko Kando · Joseph Buongiorno

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Abstract Utilization efficiency has been defined as the ratio of the amount of industrial roundwood (or wood pulp) consumed in a country and year to the amount that would have been consumed to produce the same output with a reference technology. The reference technology was described by the average input–output relationships in countries of the Organization for Economic Cooperation and Development (OECD), from 1961 to 2005. The results showed that the efficiency of industrial roundwood utilization increased in most OECD countries from 1961 to 2005. There was also a strong decrease in the amount of wood pulp used for a given level of paper and paperboard production. Regression analysis with cross-sectional data suggested that the main determinant of the differences in efficiency of wood utilization between countries was the forest area per capita. The wood pulp price and population density were the main variables explaining the differences in wood pulp utilization between countries.

Keywords Efficiency · Forest industries · International · Technical change

Introduction

Wood is an important raw material. In the United States, and annual wood production is equal to the weight of all metals, plastics, and Portland cement; and in the world, industrial roundwood production in volume exceeds that of metals (Bowyer et al. 2003).

How well this wood is used in making various products is the subject of this paper. Utilization efficiency is a necessary, though not sufficient, condition of economic efficiency in wood product industries. Efficient use of wood and wood pulp as raw materials is also an important ingredient in forest conservation. Other things being equal, less wood used at the mill means more trees saved in the forest for carbon sequestration, biodiversity, water protection, aesthetics, and other values.

Better knowledge of the production technologies is also needed in building models of the forest sector. For example, in the Global Forest Products Model (Buongiorno et al. 2003), the transformation of raw materials into wood products is described with input–output (I–O) coefficients. These coefficients are not yet accurate, and little is known regarding their change over time.

Buongiorno and Grosenick (1977) investigated the wood pulp and industrial roundwood utilization in 33 countries from 1961 and 1971. They found that the ratio of wood input to product output had decreased. Conversely, the amount of wood pulp per unit of paper and paperboard had increased slightly, suggesting an "increase [in] the share of virgin wood pulp in paper manufacturing, at the expense of secondary fiber such as recycled paper".

Ince (2000) noted that 70% of industrial roundwood harvested in the United States in the 1950s was converted into forest products. Fifty years later, this ratio had increased to 95% mainly because of the utilization of wood residues, and because of the recovery of waste paper. Berglund and Söderholm (2003) found that developed countries recovered and used more waste paper than others. Population density and urbanization had a positive effect on recovery, especially in developing countries.

H. Kando · J. Buongiorno (✉)
Department of Forest and Wildlife Ecology,
University of Wisconsin-Madison, 1630 Linden Drive,
Madison, WI 53706, USA
e-mail: jbuongio@wisc.edu

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Cardellichio (1989) explained the increase in log processing efficiency in sawmilling by the higher price of logs, the scarcity of old-growth timbers, and the size and vintage of mills. In pulp production, Yin (2000) found that most manufacturers were technically efficient in converting inputs into outputs, though inefficient in allocating inputs. Lee (2005) found that paper companies in Japan tended to be the most efficient, and those in Latin America were the least efficient.

Buongiorno et al. (2001) estimated input–output coefficients for 14 wood and paper industries in 184 countries. Their goal-programming approach allowed for adjustment of the production data that were inconsistent with a priori knowledge of the technology. They did not compare the input–output coefficients over time.

The objective of this study was to define a measure of utilization efficiency, and to use it to compare the efficiency of the transformation of industrial roundwood and wood pulp into products between countries and over time. The last part of the paper investigates some of the determinants of utilization efficiency.

Materials and methods

Measures of efficiency

The efficiency of industrial roundwood utilization, E_{it}^{R}, in a particular country, i, and year, t, relative to a reference region and period has been defined as:

$$E_{it}^{\mathrm{R}} = \frac{\mathrm{IRC}_{it}}{\widehat{\mathrm{IRC}}_{it}} \tag{1}$$

where IRC_{it} was the industrial roundwood consumed in country i and a year t, and $\widehat{\mathrm{IRC}}_{it}$ was the industrial roundwood that would have been consumed in the same country and year to produce the same amount of sawnwood, panels, and wood pulp with a reference technology. Here, the reference technology was that of the average OECD country from 1961 to 2005, described below.

The efficiency ratio Eq. 1 allowed efficiency comparisons between years in a country, between countries in a particular year, and between different countries and years. Higher ratios meant more wood used for a given output, and thus lower efficiency. Thus: $E_{it} < E_{iT}$ implied that in country i, efficiency was higher at t than at T. $E_{it} < E_{kt}$ implied that in year t, efficiency was higher in country i than in country k, and $E_{it} < E_{kT}$ implied that the efficiency was higher in country i and year t is than in country k and year T.

An analog index measured the efficiency of wood pulp utilization, E_{it}^{U}:

$$E_{it}^{\mathrm{U}} = \frac{\mathrm{WPC}_{it}}{\widehat{\mathrm{WPC}}_{it}} \tag{2}$$

where WPC_{it} was the wood pulp consumed in country i and year t, and $\widehat{\mathrm{WPC}}_{it}$ was the wood pulp that would have been consumed in the same country and year with the reference technology to produce the same amount of paper and paperboard.

Reference technologies

The reference technologies were based on data from OECD countries[1] from 1961 to 2005. The data from different years and countries were pooled in a single "panel data" set. This pooling of cross-sectional and time-series information increased the number of observations, widened the range of the dependent and independent variables, and decreased the collinearity between explanatory variables, to yield more accurate estimates of the coefficients.[2]

For industrial roundwood, the following regression equation represented the relationship between output and input:

$$\begin{aligned} \mathrm{IRC}_{it} &= \alpha \mathrm{SWP}_{it} + \beta \mathrm{PULP}_{it} + u_{it} \\ i &= 1,\ldots,N;\; t = 1,\ldots,T \end{aligned} \tag{3}$$

where IRC ($\mathrm{m}^3\ \mathrm{year}^{-1}$) is industrial roundwood consumption, SWP ($\mathrm{m}^3\ \mathrm{year}^{-1}$) is solid wood production, including sawnwood and wood-based panels (veneer and plywood, particleboard, and fiberboard). PULP ($\mathrm{t\ year}^{-1}$) is wood pulp production (mechanical, chemical, and semi-chemical). N is the number of countries, and T is the number of years in the sample. α and β are parameters, and u is an error term.

There is no constant term in Eq. 3 because the expected value of industrial roundwood consumption must be zero if both SWP and PULP are zero. Equation 3 implies that, other things being equal, a 1 $\mathrm{m}^3\ \mathrm{year}^{-1}$ change of SWP changes the expected value of IRC by α m^3 per year, and a 1 $\mathrm{t\ year}^{-1}$ change of *PULP* changes the expected *IRC* by β $\mathrm{m}^3\ \mathrm{year}^{-1}$.

An equation analog to 3 was used to establish the reference technology for the transformation of wood pulp into paper and paperboard:

[1] The main reason for restricting the data to OECD countries was to avoid large errors, especially in the production statistics (Buongiorno et al. 2001).

[2] Other reference technologies were explored, some based on pure time series, where the reference technology was defined by the data of a single country from 1961 to 2005, and others based on pure cross-sections, where the reference technology was defined by many countries in a single year. Both proved inferior to the pooling of time series and cross-sectional data in a panel, for the reasons stated here (see also Kando 2008).

$$\text{PULC}_{it} = \gamma N_{it} + \delta W_{it} + \mu O_{it} + u_{it} \quad (4)$$

where PULC is wood pulp consumption, and N, W, and O are the production of newsprint, printing and writing paper, and other paper and paperboard, all measured in metric ton per year. γ, δ, and μ are parameters.

Upon estimation of Eqs. 3 and 4 by ordinary least squares, serial correlation was observed in the error term u_{it}. To correct for this, both equations were re-estimated with the method of Hildreth and Lu (Greene 1993).

Efficiency levels, trends, and causes

To compare the efficiency level in different OECD countries we computed the average efficiency within each country from 1961 to 2005, $\bar{E}_i$, and ranked the countries accordingly. $\bar{E}_i$ higher than 1 meant that a country had been less efficient than the average OECD country from 1961 to 2005. The trend in efficiency within each country was estimated with the regression equation:

$$E_{it} = a_i + b_i t + v_t \quad t = 1961, \ldots, 2005 \quad (5)$$

where a is a constant, b is the average annual change in efficiency, and v is the error.

The following model was used to test hypotheses concerning the causes of the differences in industrial roundwood utilization efficiency between countries:

$$\bar{E}_i^{\text{R}} = \alpha + \beta A_i + \gamma \bar{Y}_i + \delta \overline{P}_i^{\text{R}} + \varepsilon \overline{Q}_i^{\text{R}} + u_i \quad (6)$$

where A is forest area per capita in 2005, $\bar{Y}$ and $\bar{P}^{\text{R}}$ are, respectively, GDP per capita and industrial roundwood price, both in constant (year 2000) US$ averaged from 1961 to 2005, and $\bar{Q}^R$ is the average industrial roundwood production per capita during the same period.

The hypothesis was that $\bar{E}^{\text{R}}$would be positively related to A, since, other things being equal, wood is more likely to be wasted were there are abundant forests. For similar reasons, $\bar{Q}^{\text{R}}$, which measures wood supply was expected to have a positive effect on $\bar{E}^{\text{R}}$. Instead, $\bar{P}^{\text{R}}$ which indicates expensive wood should induce efficient use of wood and therefore have, other things being equal, a negative effect on $\bar{E}^{\text{R}}$. $\bar{Y}$ was hypothesized to have a negative effect on $\bar{E}^{\text{R}}$ as richer countries would have more wood-saving technologies, as well as more means of conserving forests in accord with the environmental Kuznet's curve theory (Turner et al. 2006).

Similarly, potential determinants of wood pulp utilization efficiency were tested with the following regression equation:

$$\bar{E}_i^{\text{U}} = \alpha + \beta A_i + \gamma \bar{Y}_i + \delta \overline{P}_i^{\text{U}} + \varepsilon \overline{N}_i + \lambda \overline{U}_i + u_i \quad (7)$$

where $\bar{P}^{\text{U}}$ is the wood pulp price in constant (year 2000) US$ averaged from 1961 to 2005. $\bar{N}$ is the average population density over the same period. $\bar{U}$ is the average urbanization rate, that is the ratio of the urban to rural population, from 1961 to 2005.

The hypothesis was that A would have a positive effect on $\bar{E}^{\text{U}}$, as there would be less inducement to use waste paper or non-wood fibers in countries with abundant forest resources. $\bar{Y}$, instead, would have a negative effect on $\bar{E}^{\text{U}}$ as richer countries tend to recycle more (Berglund and Söderholm 2003), and thus have a larger supply of waste paper. $\bar{P}^{\text{U}}$ was also expected to be negatively related to $\bar{E}^{\text{U}}$ as countries where wood pulp price is higher would have an incentive to use less of it. Countries with higher population density, $\bar{N}$, and higher urbanization rates were expected to have lower $\bar{E}^{U}$, as the availability of waste paper would be higher, and the collection cost would be lower in those countries.

As the residuals of both Eqs. 6 and 7 had a non constant variance, their standard errors were estimated with White's (1980) heteroskedastic-robust method.

Data

The data were panel data from 1961 to 2005 from 29 OECD countries: Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Korea, Luxembourg, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Spain, Sweden, Switzerland, Turkey, the United Kingdom, and the United States.[3]

The data on forest products production, imports, and exports came from the FAOSTAT data base (FAO 2008a). For each year and country, consumption was equal to production plus imports minus exports. The industrial roundwood consumption (IRC) excluded "other industrial roundwood", which is wood used directly in roundwood form such as poles, piling, and posts. It included the net imports of chips and particles and wood residues, and excluded exports.

Solid wood production (SWP) was the sum of sawnwood[4] production, coniferous and non-coniferous, and of wood-based panels production. Wood-based panels included veneer sheets, plywood, particleboard, and fiberboard,

[3] Non OECD countries were also considered but discarded due to inaccurate data. In FAOSTAT, from 1961 to 1998, Belgium and Luxembourg were grouped as Belgium–Luxembourg, and from 1961 to 1991, the Czech Republic and the Slovak Republic were grouped as Czechoslovakia. Iceland is an OECD country, but it was not included because it did not make forest products. For the analysis of pulp utilization, Luxembourg was not included because it had no paper or paperboard production.

[4] "Wood that has been produced from both domestic and imported roundwood" (FAO 2008c).

Table 1 Input–output coefficients estimated from panel data from OECD countries from 1961 to 2005

Input	Output	Coefficient (SE)	Units
Industrial roundwood	Sawnwood and panels	$\alpha = 1.65$ (0.06)	$m^3\ m^{-3}$
	Pulp	$\beta = 2.67$ (0.17)	$m^3\ t^{-1}$
Wood pulp	Newsprint	$\gamma = 1.06$ (0.09)	$t\ t^{-1}$
	Printing and writing paper	$\delta = 1.03$ (0.06)	$t\ t^{-1}$
	Other paper and paperboard	$\mu = 0.31$ (0.03)	$t\ t^{-1}$

hard and soft.[5] Wood pulp consisted of mechanical, chemical, and semi-chemical wood pulp. It excluded other fiber pulp and waste paper.

Forest area per capita was computed with forest area data from FAO (2008b) and population data from the World Bank development indicators database (World Bank 2008). The same sources were used for industrial roundwood production per capita. GDP per capita, population density, and urbanization came from World Bank (2008). The price of industrial roundwood and wood pulp was the value of imports plus exports divided by their quantity, obtained from FAO (2008a).

Results

Input–output coefficients

The input–output coefficients of OECD countries from 1961 to 2005 obtained from the regression models 3 and 4 are in Table 1. On average, the production of 1 m^3 of sawnwood and panels required about 1.65 m^3 of industrial roundwood, and the production of 1 t of wood pulp required 2.67 m^3 of industrial roundwood. An average of 1.06 t of wood pulp was used per ton of newsprint, and 1.03 t of wood pulp per ton of printing and writing paper. Less than 0.4 t of wood pulp was consumed on average to produce 1 t of other paper and paperboard. Thus, compared to newsprint and printing and writing paper, other paper and paperboard production used more non-wood fibers or recycled paper.

Efficiency of industrial wood utilization

Using the average OECD country from 1961 to 2005 as the reference technology, the predicted industrial roundwood consumption in a particular country i and year t was given by:

$$\hat{IRC}_{it} = 1.65SWP_{it} + 2.67PULP_{it} \quad (8)$$

where SWP_{it} was the actual solid wood production, and $PULP_{it}$ was the actual pulp production. The parameters are those obtained with Eq. 3 (Table 1). With their earlier data, Buongiorno and Grosenick (1977) found a coefficient of $1.51(\pm0.02)$ for the conversion of industrial roundwood to wood-based panels, and a coefficient of $4.49(\pm0.13)$ for the conversion of industrial roundwood to pulp. Thus, the coefficients in Eq. 8 suggest an increase in efficiency, especially in the use of wood in pulp production.

Table 2 contains the time-average efficiency of industrial roundwood utilization, $\bar{E}_i$, and the average annual change in efficiency, b_i in Eq. 5, for each country, from 1961 to 2005. According to the present definition, Japan and Switzerland had been the most efficient users of

Table 2 Average level and annual change in industrial roundwood utilization efficiency in OECD countries from 1961 to 2005

Country, i	Average, $\bar{E}_i$ (SE)	Annual change, b_i (SE)
Australia	1.32 (0.04)**	−0.01 (0.01)
Canada	1.25 (0.02)**	−0.010 (0.001)**
Sweden	1.16 (0.02)**	0.001 (0.002)
Mexico	1.15 (0.02)**	−0.006 (0.001)**
Finland	1.14 (0.01)**	−0.002 (0.001)**
Portugal	1.13 (0.02)**	−0.007 (0.004)
United States	1.11 (0.01)**	−0.003 (0.002)
Ireland	1.08 (0.05)*	−0.001 (0.005)
Hungary	1.02 (0.03)	−0.005 (0.004)
Norway	1.02 (0.02)	−0.003 (0.002)*
France	1.02 (0.01)*	−0.002 (0.001)
Poland	1.01 (0.03)	0.017 (0.002)**
Spain	1.01 (0.02)	−0.001 (0.004)
New Zealand	1.00 (0.05)	−0.03 (0.01)**
Netherlands	0.90 (0.03)**	0.004 (0.003)
Italy	0.89 (0.03)**	−0.006 (0.004)
Korea	0.87 (0.03)**	−0.008 (0.003)**
Denmark	0.86 (0.07)*	0.10 (0.04)*
United Kingdom	0.83 (0.02)**	−0.005 (0.003)
Austria	0.82 (0.01)**	−0.005 (0.001)**
Germany	0.78 (0.03)**	−0.010 (0.002)**
Greece	0.78 (0.03)**	−0.009 (0.003)**
Turkey	0.77 (0.03)**	−0.01 (0.01)
Switzerland	0.75 (0.02)**	−0.007 (0.002)**
Japan	0.75 (0.01)**	0.003 (0.002)

* Average significantly different from 1, or an annual change significantly different from 0, at the 0.05 significance level

** Average significantly different from 1, or an annual change significantly different from 0, at the 0.01 significance level

[5] We assumed that the amount of veneer imported to make plywood was negligible. For example, in 2006 Japan imported 93,000 m3 of veneer, for all uses, while it produced 3,314,000 m3 of plywood (FAO 2008c).

industrial roundwood (Table 2). For their level of output, they both used 25% less industrial roundwood than the average OECD country would have used during that period. But, while the efficiency in Japan had not changed significantly from 1961 to 2005, it had improved at 0.7% per year in Switzerland.

Australia and Canada had been the least efficient. From 1961 to 2005, Australia used 32% more industrial roundwood, than the average OECD country would have used for the same level of output. Canada used 25% more (Table 2). Canada's efficiency had improved at 1% per year over the period, while Australia's had not changed significantly.

Among average performers were Poland, Spain, and New Zealand. While Spain's efficiency had not changed significantly from 1961 to 2005, the efficiency of New Zealand had improved at an average rate of 3% per year and that of Poland had decreased at 1.7% per year.

For the OECD as a whole, the efficiency of industrial roundwood utilization had improved at about 0.4% per year (Table 2). Although it is statistically highly significant, this seems to be a small improvement in practice.

Figure 1 shows the individual country data in more detail with the 3-year moving average of the efficiency ratio from 1961 to 2005. For some countries, the efficiency varied considerably around the trend calculated in Table 2. For example, Australia's efficiency ratio worsened from 1962 to 1985 and improved rapidly thereafter, ending at the same level as Canada and Finland (Fig. 1a). Denmark's index changed in the opposite direction, showing a rising efficiency from 1962 to 1985 and a rapid deterioration thereafter. The data for Ireland suggested a structural break in 1982, but similar trends of the efficiency index before

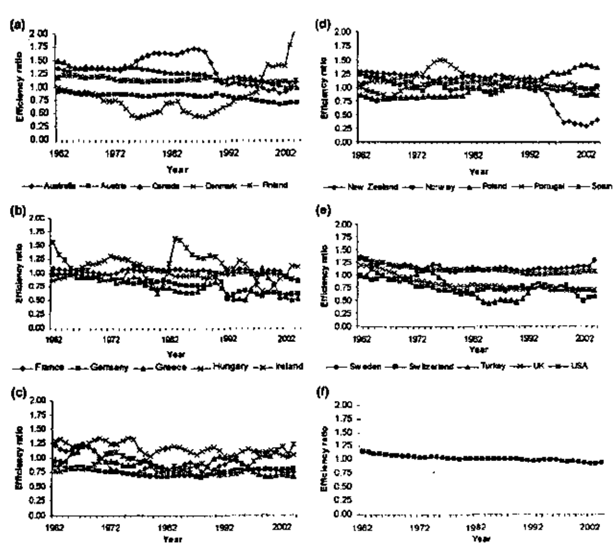

Fig. 1 Trends in industrial roundwood utilization efficiency in OECD countries

and after (Fig. 1b). New Zealand's index indicated a strong improvement in efficiency after 1992 (Fig. 1d).

For the other countries, there was a smoother evolution of efficiency over the period considered. The indices of Austria and Finland moved almost in parallel (Fig. 1a). Both indicated an improvement in efficiency. But Austria's efficiency stayed at least 25% above that of Finland. Germany's efficiency improved continuously relative to France's which changed little from 1961 to 2005 (Fig. 1b). During this period, Japan's efficiency stayed almost unchanged and at a high level relative to Mexico (Fig. 1c). Poland's efficiency declined regularly from 1961 to 2005, while Norway's moved in the opposite direction (Fig. 1d). Sweden's index indicated similar efficiency as in the United States, with little change throughout the period, while the efficiency of Switzerland and the United Kingdom improved substantially (Fig. 1e).

Efficiency of wood pulp utilization

Based on the average OECD country from 1961 to 2005 as the reference technology, the predicted wood pulp consumption in a particular country i and year t was given by:

$$\hat{\mathrm{PULC}}_{it} = 1.06N_{it} + 1.03W_{it} + 0.31O_{it} \quad (9)$$

where N_{it} is the newsprint production in country i in year t, W_{it} is the printing and writing paper production, and O_{it} is the other paper and paperboard production. The parameters are from Eq. 3 (Table 1). Buongiorno and Grosenick (1977) found that 0.86 (±0.01) ton of pulp was required for per ton of paper and paperboard ($N + W + O$). Given the shares of production shares of newsprint, printing and writing paper, and other paper and paperboard in (15, 29, and 56%), respectively, Eq. 9 implies a coefficient of 0.63 t of pulp per ton of paper and paperboard with our dataset. This suggests an increase in efficiency, presumably due to the increasing use of waste paper.

The average wood pulp utilization efficiency from 1961 to 2005 was highest in The Netherlands, followed by Denmark (Table 3). The Netherlands used 36% less wood pulp, and Denmark used 30% less, than the average OECD country used through the same period to produce the same amount of paper and paperboard. At the other extreme, Sweden and New Zealand both used 49% more wood pulp than the average OECD country to produce a given amount of output. The systematically negative annual change (Table 3) shows that wood pulp utilization efficiency had improved in all the countries from 1961 to 2005. And in most countries (the exceptions were New Zealand and Portugal), the improvement was statistically significant.

Figure 2 shows the efficiency indices by country as 3-year moving averages from 1961 to 2005. For example, Fig. 2a shows that the efficiency of Canada, Finland, and

Table 3 Average level and annual change in wood pulp utilization efficiency in OECD countries from 1961 to 2005

Country, i	Average, $\bar{E}_i$ (SE)	Annual change, b_i (SE)
Sweden	1.49 (0.03)**	−0.016 (0.002)**
New Zealand	1.49 (0.02)**	−0.005 (0.003)
United States	1.44 (0.02)**	−0.011 (0.001)**
Poland	1.38 (0.03)**	−0.02 (0.01)**
Portugal	1.24 (0.05)**	−0.006 (0.004)
Australia	1.23 (0.05)**	−0.021 (0.002)**
Turkey	1.17 (0.04)**	−0.013 (0.003)**
Finland	1.17 (0.03)**	−0.014 (0.001)**
Norway	1.17 (0.02)**	−0.011 (0.001)**
Japan	1.03 (0.04)	−0.021 (0.002)**
Canada	1.03 (0.02)*	−0.009 (0.001)**
Hungary	1.00 (0.06)	−0.02 (0.01)**
Greece	0.99 (0.06)	−0.03 (0.01)**
Austria	0.96 (0.04)	−0.018 (0.002)**
France	0.95 (0.03)*	−0.014 (0.002)**
Spain	0.95 (0.03)	−0.015 (0.001)**
United Kingdom	0.93 (0.04)*	−0.020 (0.002)**
Italy	0.87 (0.02)**	−0.008 (0.003)*
Korea	0.86 (0.10)	−0.03 (0.01)**
Germany	0.84 (0.04)**	−0.018 (0.002)**
Mexico	0.77 (0.04)**	−0.015 (0.003)**
Switzerland	0.77 (0.03)**	−0.013 (0.001)**
Denmark	0.70 (0.04)**	−0.02 (0.01)**
Netherlands	0.64 (0.02)**	−0.012 (0.002)**
All OECD	1.00 (0.01)	−0.004 (0.0004)**

* Average significantly different from 1, or an annual change significantly different from 0, at the 0.05 significance level

** Average significantly different from 1, or an annual change significantly different from 0, at the 0.01 significance level

Australia have been converging, reaching about the same level around 2002. By that time, all three countries used substantially more wood pulp than Austria and Denmark for a given level of output. Figure 2b shows the more rapid increase in efficiency in Germany than in France, analog to what was observed for industrial roundwood. From around 1962 to 2004, Japan's wood pulp utilization had decreased from 37% above to 33% below that used by the average OECD country during that period (Fig. 1c). Meanwhile, the utilization in New Zealand had cycled at a much higher level than in Japan, without a significant trend. Figure 1c also suggests erroneous data for the Republic of Korea around 1962, and later a convergence of Korea's efficiency towards that of the Netherlands, the most efficient user of wood pulp according to the present definition. There was also a convergence of the efficiencies of Norway, Poland, Portugal, and Sweden in the most recent years; however, Spain continued to use much less pulp than these countries,

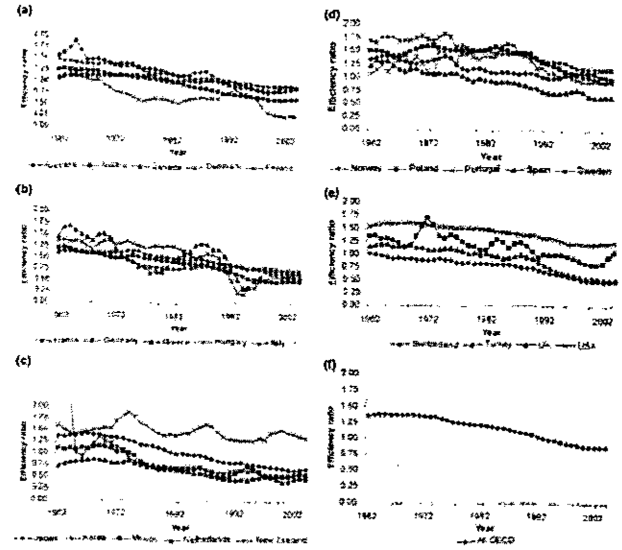

Fig. 2 Trends in wood pulp utilization efficiency in OECD countries

as it had in most previous years (Fig. 1d). The efficiencies of the United States and Switzerland had changed almost in parallel from 1961 to 2005 (Fig. 1e), wood pulp utilization being much higher in the United States. By the end of this period, the United Kingdom's efficiency had almost converged with that of Switzerland.

Determinants of utilization efficiency

The results of estimation of Eqs. 6 and 7 are in Table 4. For industrial roundwood, the three explanatory variables accounted for 55% of the variation in utilization efficiency between countries. The three variables had coefficients of the expected sign. Wood utilization efficiency was lower in countries that had more forest area per capita and higher production of industrial roundwood per capita. It was higher in countries with high GDP per capita and higher industrial roundwood price. However, only the forest area per capita had a statistically significant effect.

For wood pulp, the five explanatory variables accounted for 48% of the variation in utilization efficiency. Four of the five variables had coefficients of the expected sign. The exception was the positive coefficient of GDP per capita, but it was not significantly different from zero. Utilization efficiency was significantly higher in countries of high wood pulp price and high population density.

Summary and conclusion

This study dealt with the international utilization of industrial roundwood and wood pulp in the manufacture of forest products. It led to indices that allowed comparison of utilization efficiency between countries and over time.

Table 4 Effect of selected variables on the utilization efficiency of industrial roundwood and wood pulp in OECD countries

Input	Explanatory variables	Coefficients[a]
Industrial roundwood	Forest area per capita	0.04 (0.01)**
	GDP per capita	−0.006 (0.003)
	Industrial roundwood price	−0.10 (0.61)
	Industrial roundwood production per capita	0.01 (0.01)
	R^2	0.55
Wood pulp	Forest area per capita	0.003 (0.016)
	GDP per capita	0.003 (0.006)
	Wood pulp price	−1.77 (0.64)*
	Population density	−0.0009 (0.0003)**
	Urbanization	−0.005 (0.004)
	R^2	0.48

* Coefficients significantly different from zero at 0.05 significance level

** Coefficients significantly different from zero at 0.01 significance level

[a] Numbers in parentheses are heteroskedastic-robust standard errors

Utilization efficiency in a country and year was defined as the ratio between the industrial roundwood or wood pulp that was consumed and the amount that would have been consumed to produce the same output with a reference technology. The reference technology was the average relationship between input and products in OECD countries from 1961 to 2005.

The results suggested that the utilization of wood had improved in most OECD countries from 1961 to 2005. There was also a strong decrease in the amount of wood pulp for a given level of paper and paperboard production.

Among the variables investigated, the availability of wood, expressed by forest area per capita, was the main reason for the differences in wood utilization efficiency. The superior efficiency in wood pulp utilization in some countries was explained in part by higher price of wood pulp and high population density, both of which induce higher waste paper supply.

This study has dealt only with the technical efficiency of wood and fiber use. Technical efficiency is necessary, but not sufficient for economic efficiency. A full assessment of changes in efficiency over time, and comparison of efficiency between countries, should recognize the relative cost of all input (including labor, capital, and energy), and the value of output. Economic efficiency has been studied for a few countries and forest industries (e.g., Hseu and Buongiorno 1994). One useful aspect of the results presented here is to show the wide range of technical possibilities that can be exploited by industries in seeking economic efficiency.

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