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Technical Change in the North American Forestry Sector: A Review

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ABSTRACT. Economists have examined the impact of technical change on the forest products sector using the historical, index number, and econometric approaches. This paper reviews econometric analyses of the rate and bias of technical change, examining functional form, factors included, and empirical results. Studies are classified as first- second-, or third-generation approaches. First-generation studies are based on simple value-added measures of output, usually employ simple functional forms to represent the production technology, and incorporate only capital and labor inputs. Second-generation studies are characterized by estimation of more complex, flexible dual cost or profit functions and typically include resource and often energy inputs. Third-generation studies also rely upon dual formulations of the production structure and include multiple factors; however, in addition they specify the dynamics of adjustment of quasi-fixed factors over time. The studies reveal a tradeoff between the richness of the theoretical structure of the production technology and the consistency of the empirical results. Most studies have reported a labor-saving and energy-using bias to technical change, but little or no wood-saving bias, and many report a wood-using bias. Since technical advances occur in spurts, the use of a simple linear time trend to represent the state of technology is a major limitation of virtually all models. Alternative measures, such as the power ratings or throughput measures, might better capture the characteristics of a technology. Use of such measures might also be combined with a cross-sectional approach in an attempt to avoid some of the statistical problems, such as serial correlation, that characterize time series data. Finally, if the goal of the analysis is to forecast factor demand and cost implications of technical change, simulation models may offer a more promising alternative. FOR. SCI. 38(1):134–159.

ECONOMISTS FIRST ATTEMPTED TO MEASURE THE CONTRIBUTION of technical change to economic growth in the mid-1950s (Abrahamovitz 1956, Schmookler 1952, Solow 1957, Ruttan 1956). The main focus of these early studies was on differentiating quantitatively between the contribution of technical change and that of increases in capital and labor on growth in output. The findings of these and subsequent studies indicated that technical change—defined broadly as the application of new knowledge to production processes—was primarily responsible for economic growth in the long-run. Only a small proportion of the growth of output in the economy could be explained by increases in the quantities of labor and capital. For example, Solow's (1957) classic study concluded that 87.5% of per capita growth could be attributed to technical change versus only 12.5% to increases in the capital stock.

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Following the early economy-wide studies, economists began examining the rate and direction of technical change in specific sectors and industries. The first empirical studies of technical change in the forest-based sector did not appear until the early 1960s (Ruttan and Callahan 1962). A relatively large number of such studies has now been carried out, and it is perhaps appropriate to step back and review the work that has been done in this field.

To put this review in context, studies of biased technical change reviewed here are part of a much larger body of research on the economics of technical change. This larger field includes four main subject areas[1]: (1) the generation of new technology, e.g., models of research and development determination, studies of the sources of new technology (Guttman 1978, Scherer 1982, Robson et al. 1988); (2) the rate and bias of technical change, which includes the studies reviewed in this paper as well as studies of the induced innovation hypothesis (Link 1983); (3) the diffusion of new technology, both from the standpoint of intra- and interfirm diffusion and international diffusion (Globerman 1976, Buorngiorno and Oliveira 1977, Leefers 1981, Stier 1983b, Spelter 1985, Montrey and Utterback 1990, Hjelm 1991); and (4) the economic impacts of technical change, which include studies of the efficiency and distributional impacts and returns to investment in research and development (R&D). This latter area has been the subject of much research in the past decade. The evaluation methodology is reviewed in Bengston (1985) and Seldon (1987a) and representative studies include Bengston (1984), Westgate (1986), Haygreen et al. (1986), Seldon (1987b), Seldon and Newman (1987), Stier (1990), Newman (1990b), and Seldon and Hyde (1991a, 1991b). Herrick (1982) and Skog and Haynes (1987) also look at the impacts of technical changes on the costs of production, but do not consider the supply (cost) aspects of achieving those changes.

The purpose of this paper is to review and assess empirical studies of the rate and direction of technical change in the North American forest industries, with the primary focus on the more recent econometric studies of the effect of the bias of technical change on the demand for factors of production in forestry. To illustrate such effects, in the absence of changes in the prices of inputs, labor-saving technical change would displace labor independently of reductions in the level of timber harvest, and a wood-saving bias would permit greater output to be produced from a fixed level of roundwood input. Both of these phenomena have been reported for some segments of the forestry sector (Lange et al. 1990, Rosenberg et al. 1990, Xu et al. 1990), and long-term projections of stumpage supply and demand are likely to be seriously flawed unless they incorporate such effects (Rosenberg et al. 1990).

The paper is organized as follows. In the next section key terms are defined and the main approaches which have been used to measure technical change in the forest industries are reviewed. Next, econometric studies are reviewed and summarized. This body of research is then evaluated in terms of both technical and policy perspectives. Finally, some implications for future research on technical change in the forest industries are discussed.

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[1] Representative studies in each of the areas are cited in parentheses. See Bengston and Gregersen (1991) for a more detailed overview of the economics of technical change in the forest-based industries. There has been very little work of the first type in forestry and forest products compared to other fields and this would seem to be a fruitful area for future research.

DEFINITIONS

Technical change was defined above as the application of new knowledge to production processes. Other definitions have been proposed. For example, Ruttan (1982, p. 237) gives the following definitions: (1) technical change is the substitution of "inexpensive and abundant resources for scarce and expensive resources," (2) technical change is "the substitution of knowledge for resources," and (3) technical change "releases the constraints on growth imposed by inelastic resource supplies."

Ruttan's first definition seems to reflect standard factor substitution within the context of a given technology, but he was referring to the changes in a production process necessary to bring about the potential for such substitution. This interpretation is supported by his reference to knowledge, i.e., innovations, in his second definition and the "release of constraints on growth" in the third. It is this recognition that technical change is a dynamic attempt to overcome constraints, i.e., to change the *parameters* of the production process, that differentiates between factor substitution within the context of a given production technology and a change in the technology itself.

To reflect the above concepts, we adopt the common definition of technical change as an upward shift in the production function or a movement of the isoquants towards the origin. Thus, the rate of technical change can be measured either as the increase in output obtained from the same quantities of inputs, or equivalently, the decrease in inputs needed to produce a given level of output.

Neutral and biased technical change: Technical change is unlikely to affect the demand for all inputs[2] equally, but if it does, it is referred to as "neutral." In most cases, however, it appears that technical change is biased. In the Hicksian sense, the technical change bias for a simple two-input production process is defined to be "labor-saving, labor-neutral, or labor-using depending on whether, at constant factor prices, the labor-capital ratio decreases, stays constant, or increases" (Binswanger 1978, p. 20). This definition can be summarized mathematically as:

$$\frac{\partial(k)}{\partial t} \cdot \frac{1}{(k)} \begin{cases} >0 \Rightarrow \text{labor-saving} \\ =0 \Rightarrow \text{neutral} \\ <0 \Rightarrow \text{capital-saving} \end{cases} \tag{1}$$

where k is the capital-labor ratio, and t is an index of the state of technology. If more than two factors are involved, the rate of the bias for the ith factor is defined as:

$$\frac{\partial(S_i)}{\partial t} \cdot \frac{1}{(S_i)} \begin{cases} <0 \Rightarrow i\text{-saving} \\ =0 \Rightarrow i\text{-neutral} \\ >0 \Rightarrow i\text{-using} \end{cases} \tag{2}$$

where S_i is the share of the ith factor in total cost and relative factor prices are again held constant.

[2] The terms "inputs," "factors of production," and "factors" are used interchangeably throughout the paper.

In contrast, the ease with which one factor (i) can be substituted for another (j) within the confines of a given multifactor production technology has typically been measured by the Allen/Uzawa elasticity of substitution (σ_{ij})

$$\sigma_{ij} = \frac{C(y, p)C_{ij}(y, p)}{C_i(y, p)C_j(y, p)} \tag{3}$$

where C is total cost, y is output, p is a vector of factor prices, and the subscripts on C refer to partial derivatives with respect to the prices of factors i and j. The elasticity of factor substitution is related to the constant output cross-price elasticity of factor demand (ϵ_{ij}) in the following manner

$$\sigma_{ij} = \frac{\epsilon_{ij}}{S_j} \tag{4}$$

where ϵ_{ij} is the cross-price elasticity of demand for the ith factor with respect to the price of the jth factor, and S_j is the share of the jth factor in total cost.[3]

Blackorby and Russell (1989) showed that the Allen/Uzawa elasticity of factor substitution has a number of theoretical limitations and that the cross-price elasticity of factor demand (ϵ_{ij}) contains no information not already revealed by the elasticity of factor substitution (σ_{ij}). They argue the superiority of the Morishima elasticity of factor substitution (σ'), which is calculated as

$$\sigma'_{ij} = \frac{p_i C_{ij}(y, p)}{C_j(y, p)} - \frac{p_i C_{ii}(y, p)}{C_i(y, p)} \tag{5}$$

where variables are as defined above, and p_i is the price of the ith factor. In this case, the cross-price elasticity of factor demand for the jth factor with respect to the ith factor price (ϵ_{ji}) is related to σ' as

$$\sigma'_{ij} = \epsilon_{ji} - \epsilon_{ii} \tag{6}$$

where ϵ_{ii} is the own price elasticity of demand for the ith factor. Unlike the Allen/Uzawa elasticity of factor substitution, the Morishima elasticity is inherently asymmetric unless the production function is of the CES-Cobb-Douglas type (Blackorby and Russell 1989).

MEASURING TECHNICAL CHANGE

This section briefly summarizes three methods which have been used to measure technical change in the forest industries; viz., the historical, index number, and econometric approaches.

Historical Approach

Historians of technology have pursued an inductive approach to understanding technical change, an approach that is often ignored by economists. In part, the

[3] Varian (1978) gives a more complete discussion of the parameters of a production technology and their significance in economic terms.

historical approach involves a detailed enumeration of the sequence and timing of innovative activity for a particular field or industry. But this is more than a simple chronological narrative of the development of "hardware" (technical devices and processes). Rather, it involves developing a theoretical framework which links technical innovations to some general principles. The theoretical framework that has most often guided the work of economic historians is induced innovation theory; i.e., the idea that technical change is stimulated by relative factor scarcities and that it attempts to alleviate those scarcities (see Thirtle and Ruttan 1987). The theory of induced innovations relates to the process that focuses general economic incentives in such a way as to yield specific technical changes, but this process cannot be understood fully without historical studies of how the focusing occurs. Cohen (1984, 1987), McGovern (1984), Rosenberg (1972, 1973), Anderson (1987), and Rosenberg et al. (1990) provide examples of this type of historical analysis of forest industries.

The historical approach provides rich insights into how technological constraints are overcome and the conditions that lead up to the successful relaxation of those constraints. However, it does not yield a quantitative measure of the rate or bias of technical change, nor does it represent a standardized "model" which can be applied directly from one situation to another in the same way as the index number or econometric approaches can.

INDEX NUMBER APPROACH

Partial productivity measures, such as indexes of labor productivity, reflect changes in the average product of the factor of interest (see for example Ruttan and Callahan 1962, Kaiser 1971, Duke and Huffstutler 1977, Sandoe and Wayman 1977, and Farris 1978). More recent work has relied on total factor productivity indexes, which relate changes in output to changes in all inputs.

The earliest studies examining the contribution of technical change to total factor productivity in the forest industries used Solow's (1957) index number method to estimate the rate of technical change based on a value-added Cobb-Douglas production function and the assumption of neutral technical change. Using this approach, Manning and Thornburn (1971) reported annual rates of technical change of approximately 2.0% for the Canadian pulp and paper industry and 0.3% for the wood products industry for the period 1940–1960. Robinson (1975) analyzed the performance of the U.S. lumber and wood products industry from 1949–1970 and found technical change to have occurred at the rate of 1.75% per year. In Risbrudt's (1979) study of four 4-digit U.S. forest industries, the rate of technical change from 1958 to 1974 ranged from a low of 0.9% in the pulping industry to a high of 2.2% in the sawmill industry.

The indexes reported by these authors are measures of total factor productivity (TFP), which is defined as the ratio of an index of outputs to an index of aggregate inputs. This concept can be applied to single or multi-output, multi-input production technologies, but the early studies cited above were based on a single output and just two inputs; viz., capital and labor.

Index number formulas differ mainly in how the individual outputs and inputs are weighted in constructing the aggregate measure of productivity, and recent research has established a link between index formulas and particular forms of production functions. The widely used Laspeyres index, for example, is appropriate if the production function is linear and all factors are perfect substitutes. More recently, researchers have tended to employ the Tornqvist index, which corresponds to a homogeneous translog production function. Selection of a particular index number formula, therefore, involves an implicit assumption about the form of the production function.

The index number approach to measuring technical progress has several advantages over the econometric approach; it is simpler to evaluate and does not suffer from limitations on degrees of freedom. Nor does it require data on factor prices if expenditure data are available. On the other hand, the approach also has its drawbacks.

All index number formulas embody the assumption of linear homogeneity in production. Index numbers do not provide any information on other production parameters of interest, such as the elasticities of factor substitution. The index of technical progress is an aggregate of the effects of all factors. Finally, if there exist increasing or decreasing returns to scale, it is not possible to separate technical change effects from scale effects without resorting to further analysis based on econometric techniques.

Recent studies using the index number approach have taken the extra step of attempting to isolate the effects of economies of scale as well as several other variables on the rate of total factor productivity. Ghebremichael et al. (1990) estimated the rate of change in total factor productivity in the lumber industries in Quebec, Ontario, and Coastal and Interior British Columbia from 1962 and 1985. The rates of TFP ranged from a low of 0.4% per year in Coastal British Columbia to a high of 1.8% in Ontario. However, when they regressed these rates on output, number of firms and a time trend to try to isolate the pure technical change effect, they reported "nonsensical results" due to the highly cyclical nature of the capital series. And when they used changes in the rate of variable factor productivity, i.e., a measure based on changes in only variable inputs, the coefficient of the time trend was statistically insignificant. Therefore, they concluded that there was no significant "pure" technical change effect, but that there were economies of scale. Yet, this latter condition violates a basic assumption underlying the index number approach.

In a somewhat similar analysis, Constantino and Haley (1989) compared trends in total factor productivity in the U.S. Douglas-fir region and the British Columbia coastal region. The authors used a quality adjusted measure of wood input, which they computed as a weighted average of sawlog volume by grade. Their results indicated that over the period 1957 to 1982, total factor productivity increased in the U.S. region by 1.24% per year. However, in the British Columbia coastal industry it increased at an annual rate of only 0.24% over the comparable period, and the rate was actually negative during the period 1971–1982. These trends were attributed to a decline in the quality of the wood input in the U.S. during the latter period versus an increase in wood quality in British Columbia. When these changes in wood quality were taken into account, the U.S. industry was shown to be significantly more productive than its Canadian counterpart.

The most recent studies to use the index number approach have combined it with econometric estimation of the total and/or variable cost function. For example, Frank et al. (1988) used a total factor productivity approach to examine the rate of technical progress in the Canadian pulp and paper industry over the period 1963–1982. They estimated that total factor productivity increased at the rate of

0.7% per year. However, when they estimated total and variable cost functions in an attempt to isolate the effects of changes in scale of output, capital stock and investment variables, they found the pure technical change effect on cost to be only 0.25% per year.

In a subsequent analysis of the Canadian pulp and paper industry using the same methods as Frank et al., but for the period 1970–1980, Oum et al. (1990) reported a rate of technical change of 0.8% per year after adjusting for changes in other variables. This was in marked contrast to the U.S. pulp and paper industry for which the annual rate of change was estimated to be 2.3%.

Researchers seem to be gravitating toward using a hybrid strategy which combines the index number and econometric approaches. We turn our attention now to the latter.

Econometric Approach

While there is a strong correspondence between index numbers and production functions, there are considerable advantages to explicit estimation of production parameters using the econometric approach. The parameters of greatest interest include the nature and extent of factor relationships as measured by (1) the elasticities of factor substitution (2) returns to scale, and (3) the extent and bias of technical change. Early efforts to estimate the effects of technical change on factor demand in the forest industries relied upon relatively simple forms of the production function. Consequently, these studies incorporated many restrictive assumptions about the nature of the production technology.

The search for functional forms which incorporate fewer maintained hypotheses about the nature of the production technology led to the discovery of flexible functions, such as the translog (Christensen et al. 1973), the generalized Leontief (Diewert 1971) and the generalized Box-Cox (Berndt and Khaled 1979), all of which permit empirical testing of the nature of the effects of factor substitution, returns to scale, and technical change. Concurrently, greater appreciation of the duality between "well-behaved" production technologies and their dual cost and profit functions enabled researchers to choose from a number of indirect approaches to estimate the parameters of interest.

The dual approach permits the behavioral response equations, including output supply and factor demand, to be obtained by simple differentiation of the respective cost or profit function. This is algebraically simpler than if one starts with the production function directly, and permits use of more complex functional forms which impose fewer maintained hypotheses on the structure of production. Consequently, the development of flexible functional forms in conjunction with duality theory greatly enriched the range of choice among models and approaches available for estimating production technologies. Indeed, it is the existence of this choice of approaches that has been called duality theory's greatest contribution to empirical work (Chambers 1982).

REVIEW OF ECONOMETRIC STUDIES

The production structure of the forest products industries has been estimated econometrically with models which impose *a priori* the assumption of neutral technical change (See, for example, Rao 1981, Singh and Nautiyal 1986, Nautiyal and Singh 1986, and Constantino and Townsend 1989). However, since this assumption can be tested statistically if the estimation is done with more general models which do permit biased technical change, this review concentrates principally on the latter, more general set of studies. The effect of technical change on the primary production of timber as a crop has, however, only been explored within the context of neutral technical change, and for that reason these studies are reviewed as well. All of these studies are based on conditions in the United States.

Newman (1986a, 1986b) hypothesized an aggregate timber production function for the 12 states in the U.S. South. He used inventory and growth as measures of output of the production process. Inputs were biological variables (average stocking, site quality, and tree diameter), area of timber type (planted and natural pine and mixed oak-pine stands) by ownership (public, industry, and nonindustrial private), and a time dummy variable to reflect changes in productivity between inventories. Newman found the coefficients of the time dummy variables to be statistically significant for both measures of output, and that over the 35-year period of the analysis the average rate of technical change was on the order of 0.5%–0.8% per year. In a similar analysis using additional inventory data for the same 12 states, Newman (1990a) found that the rate of technical change averaged 0.5% over a 40-year period.

Wallace and Newman (1986) used the same approach but limited their analysis to data from North Carolina for a 10-year period. They aggregated county data to the state level, but preserved regional differences by using dummy variables to represent interregional differences. Separate models were estimated based on the data from the 1974 inventory, the 1984 inventory, and both inventories combined. When timber inventory was taken as the measure of output, the technical change coefficient was not significant. However, when growth was used as the output measure, the rate of technical change was −0.7% per year from 1974–1984. The authors noted that the latter result was consistent with recent Forest Service data showing a decline in pine growth in the South in recent years.

The coefficients of the time dummy variables reported in these studies reflect the influence of more than just technical change; e.g., changes in environmental factors and in management intensity. The authors were aware of these limitations, and noted that the coefficients could be overestimates as well as underestimates of the actual rate of technical change. While the models used in these analyses of timber production are innovative, it is not clear exactly what is being measured by the coefficients of the time variables.

For the remainder of this review, we focus on econometric studies of the timber harvesting and manufacturing industries, and more specifically on those studies which have explicitly considered the potential for biased technical change. A summary of these studies appears in Table 1. The theoretical and empirical approaches differ among studies, and for purposes of discussion they might be conveniently classified into first-, second-, and third-generation studies.

First-generation studies are based on a simple value-added measure of output and consider only capital and labor as productive factors. Second-generation studies permit more complex representations of the production technology by extending the range of factor inputs to include raw materials and by relying on flexible functional forms. While second-generation studies can involve direct estimation of the primal production function, typically they exploit duality theory and base the

TABLE 1.

Summary of econometric studies of nonneutral technical change in the North American forest industries.

No.	Study	Industry	County/area	Time period	Model	Estimating equations	Generation model
1.	Moroney (1968)	Paper & Allied Products (SIC 26)	U.S.	1942–57	CES production function	Cost minimizing K/L ratio	First
		Lumber & Wood Products (SIC 24)					
2.	Stier (1980a)	Ten SIC 3-digit industries	U.S.	1958–74	Translog total cost function	Factor shares	First
3.	Stier (1980b)	Sawmills & Planing Mills (SIC 242)	U.S.	1950–74	Translog average cost function	Cost and factor share equations	Second
4.	Cain & Paterson (1981)	Lumber & Wood Products (SIC 24)	U.S.	1850–1919	Translog average cost function	Factor shares	Second
		Paper & Allied Products (SIC 26)					
5.	Jorgenson & Fraumeni (1981)	Lumber & Wood Products (SIC 24)	U.S.	1958–74	Translog price function	Factor share and rate of technical change equations	Second
		Paper & Allied Products (SIC 26)					
6.	Greber & White (1982)	Lumber & Wood Products (SIC 24)	U.S.	1951–73	CES production function	Rate of change of factor prices	First
7.	Stier (1982)	Logging Camps & Contractors (SIC 2411)	U.S.	1951–74	CES production function	Cost minimizing K/L	First
					Translog total cost function	Factor shares	
8.	Sherif (1983)	Pulp & Paper Mills (SIC 271)	Canada	1958–77	Translog total cost function	Cost and factor share equations	Second
9.	Stier (1983a)	Lumber & Wood Products (SIC 24)	U.S.	1951–73	CES production function	Cost minimizing K/L ratio	First

TABLE 1. Continued.

No.	Study	Industry	County/ area	Time period	Model	Estimating equations	Generation model
10.	Rao & Preston (1984)	Wood Industries (SIC 25)	Canada	1957–79	Translog total cost function	Cost and factor share equations	Second
		Paper & Allied Products (SIC 27)					
11.	De Borger & Buongiorno (1985)	Paper Mills (SIC 262)	U.S.	1958–81	Translog variable cost function	Cost and factor share equations	Second
		Paperboard Mills (SIC 263)					
12.	Martinello (1985)	Logging (SIC 031)	Canada	1963–82	Translog total cost function	Cost and factor share equations	Second
		Sawmills, Planing Mills, & Shingle Mills (SIC 251)					
		Pulp & Paper Mills (SIC 271)					
13.	Merrifield & Haynes (1985)	Lumber & Wood Products (SIC 242)	U.S.–PNW Eastside	1950–79	Translog total cost function	Cost and factor share equations	Second
		Lumber & Wood Products (SIC 242)	U.S.–PNW Westside				
		Veneer & Plywood (SIC 243)	U.S.–PNW Eastside				
		Veneer & Plywood (SIC 243)	U.S.–PNW Westside				
14.	Stier (1985)	Paper & Allied Products (SIC 26)	U.S.	1948–76	Translog total cost function	Cost and factor share equations	Second
15.	Merrifield & Singleton (1986)	Sawmills & Planing Mills (SIC 242)	U.S.–PNW	1954–80	Dynamic quadratic variable cost function	Factor demands	Third
		Veneer & Plywood (SIC 243)					
16.	Abt (1987)	Sawmills & Planing Mills (SIC 242)	U.S.–PNW	1963–78	Translog variable cost function	Cost and factor share equations	Second

TABLE 1. Continued.

No.	Study	Industry	County/ area	Time period	Model	Estimating equations	Generation model
17.	Martinello (1987)	Sawmills & Planing Mills (SIC 2512)	Canada–B.C. Coast	1963–79	Translog total cost function	Cost and factor share equations	Second
		Sawmills & Planing Mills (SIC 2512)	Canada–B.C. Interior				
		Shingle & Shake (SIC 2511)	Canada–B.C. Coast				
		Veneer & Plywood (SIC 252)	Canada–B.C. Interior				
18.	Chang (1988)	Paper & Allied Products (SIC 26)	U.S.	1950–84	Generalized Leontief total cost function	Wood factor demand	Second
19.	Constantino & Haley (1988)	Sawmills, Planing Mills & Shingle Mills (SIC 2511)	Canada–B.C. Coast	1957–82	Translog normalized variable profit function	Profit, output supply and factor demand equations	Second
		Sawmills & Planing Mills (SIC 242)	U.S.–PNW				
20.	Meil & Nautiyal (1988)	Sawmills & Planing Mills (SIC 2512)	Canada–B.C. Coast	1968–84	Translog variable cost function	Cost and factor share equations	Second
			Canada–B.C. Interior				
			Canada–Ontario				
			Canada–Quebec				
21.	Meil et al. (1988)	Sawmills & Planing Mills (SIC 2512)	Canada–B.C. Interior	1948–83	Dynamic translog variable cost function	Cost and factor share equations	Third
22.	Bernstein (1989)	Pulp & Paper (SIC 271)	Canada	1961–84	Dynamic translog normalized variable profit function	Profit, output supply and factor share equations	Third
23.	Wear (1989)	Lumber & Wood Products (SIC 24)	U.S.–Montana	1958–78	Quadratic normalized total cost function	Factor demands	Second
24.	Quicke et al. (1990)	Paper Mills (SIC 262)	U.S.	1958–85	Translog variable cost function	Cost and factor share equations	Second

actual estimation upon relationships derived from the dual profit or cost function. This procedure permits the researcher to test assumptions about the behavior of the firms or industry under study. All the second-generation studies reported in Table 1 relied upon dual functions rather than estimating the production function directly.

Finally, third-generation studies carry the theory one step farther by combining short-run cost minimizing or profit maximizing behavior with the dynamics of firm or industry adjustment of quasi-fixed factors over time. These studies provide a rich array of information on the structure of the production technology and how it changes over time in response to scale, factor substitution, and technical change effects. While third-generation studies of the forest products industries are uncommon, three examples are represented in Table 1.

First-Generation Studies

All first-generation studies pertain to U.S. forest products industries. Four of the studies in Table 1 (1, 6, 7, 9) share some common features: all were based on a constant elasticity of substitution (CES) production function, all were limited to just two factors of production (capital and labor), all based the estimation of the technical change bias upon relationships derived from the first-order conditions for efficiency in production (i.e., changes in either the factor use ratio or factor prices), and all found the technical change bias to be either capital-using and labor-saving or to be nonsignificant, with the former result being the rule. When significant, the rate of labor-saving technical change was approximately 1.5% per year.

The remaining study (2) was based on a translog dual cost function, but also employed a value-added measure of output. Technical change was estimated to be significantly capital-using and labor-saving in eight of the ten three-digit forest products industries analyzed, with the rates of change typically falling between 1.5% and 2.0% per year. Two exceptions, the "Wooden Container (SIC 244)" and "Building Paper and Bond (SIC 266)" industries, were characterized by neutral technical change.

The first-generation studies in Table 1 have inherent limitations. One of the most severe is that the models based on the CES production function are underidentified in that they are capable of yielding an estimate only of the net differential between the technical change bias of capital and labor rather than estimates of the biases for individual factors. In addition, they require the imposition of linear homogeneity on the CES production function, thus ruling out the possibility of scale effects. If such effects are present, the estimated rate of technical change will include them and will be biased.

The identification of individual technical change biases and scale effects is possible with models based on the dual translog function. However, the use of value-added as the measure of output neglects the important role of raw materials in the production process. Hence, it is also desirable to expand the vector of factor inputs to include materials and to use gross output as the measure of production.

Second Generation Studies

All but one of the 16 second-generation studies in Table 2 estimated the parameters of the production technology from the dual cost function; the lone exception

TABLE 2.

Results of second-generation technical change studies.

SIC code[a]	Forest industry	Study[b]	Time period	Region	Technical change bias[c]
24	Lumber & Wood products	4	1850–1919	US	K^{o},L^{-},M^{+},R^{o}
		5	1958–74	US	$K^{+},L^{+},E^{o}\ M^{o}$
		10	1957–79	Canada	K^{-},L^{o},E^{o},M^{+}
		23	1958–78	U.S.–Montana	L^{o},W^{-}
241	Logging Camps & Contractors	12	1963–82	Canada	K^{+},L^{-},E^{o},W^{o}
242	Sawmills & Planing Mills	3	1950–74	US	K^{+},L^{-},W^{o}
		12	1963–82	Canada	K^{+},L^{-},E^{o},W^{-}
		13	1950–79	US-PNW Eastside	$K_s^{o},K_e^{o},L^{o},W^{-}$
		13	1950–79	US–PNW Westside	$K_s^{o},K_e^{o},L^{o},W^{o}$
		16	1963–78	US–PNW	L^{-},W^{+}
		16	1963–78	US–Southeast	L^{-},W^{-}
		16	1963–78	US–Appalachian Hardwood	L^{-},W^{+}
		17	1963–79	British Columbia Coastal	K^{+},L^{-},W^{o}
		17	1963–79	British Columbia Interior	K^{+},L^{-},W^{-}
		19	1957–82	US–PNW	L^{+},W^{+}
		19	1957–82	British Columbia	L^{+},W^{+}
		20	1968–84	British Columbia Coastal	L^{o},E^{o},W^{o}
		20	1968–84	British Columbia Interior	L^{-},E^{o},W^{o}
		20	1968–84	Ontario	L^{o},E^{o},W^{o}
		20	1968–84	Quebec	L^{o},E^{o},W^{o}
243	Veneer & Plywood	13	1950–79	PNW Eastside	$K_s^{o},K_e^{-},L^{o},W^{o}$
		13	1950–79	PNW Westside	$K_s^{+},k_e^{-},L^{-},W^{o}$
		17	1963–79	British Columbia	K^{+},L^{-},W^{o}
26	Paper & Allied Products	4	1850–1919	US	K^{+},L^{o},M^{+},R^{+}
		5	1958–74	US	K^{-},L^{o},E^{+},M^{o}
		14	1948–76	US	K^{+},L^{o},W^{+}
		18	1950–84	US	W^{o}
		8	1958–77	Canada	K^{+},L^{-},E^{+},W^{-}
		10	1957–79	Canada	K^{-},L^{o},E^{+},M^{o}
		12	1963–82	Canada	K^{+},L^{-},E^{+},W^{-}
262	Paper Mills, Except Building Paper Mills	11	1958–81	US	L^{-},E^{+},M^{o}
		24	1958–85	US	L^{-},E^{+},M^{-}
263	Paperboard Mills	11	1958–81	US	L^{o},E^{o},M^{o}

[a] SIC codes and industry titles follow the U.S. Department of Commerce system.
[b] Numbers refer to the studies listed in Table 1.
[c] K = capital, K_s = capital structures, K_e = capital equipment, L = labor, E = energy, W = wood, R = residual inputs, M = materials, + = factor i-using, − = factor i-saving, o = no significant bias.

(19) employed the dual profit function. Most studies were based on the translog functional form, but the quadratic and generalized Leontief forms are also represented. While all studies include at least three factors of production, earlier models exhibit a tendency to include fewer factors and to estimate only the derived factor share equations, whereas later studies often include a wider range of inputs and incorporate the cost or profit function into the system of equations estimated.

Approximately two-thirds of the studies focus on U.S. forest products industries, with the sawmill industry having drawn particular attention in both the U.S. and Canada. If there is any generalization that can be made about these studies, it is that they are characterized by widely conflicting results.

Solid Wood Products Industries

There have been four studies of the aggregate solid wood product industry, which is known as SIC 24 "Lumber and Wood Products" in the United States, and as SIC 25 "Wood Industries" in Canada. Of the four, one was Canadian (10), two were for the U.S. as a whole (4, 5), and one was based on data for the state of Montana (23).

The studies by Cain and Paterson (4) and Wear (23) are unique. The former reported a strong labor-saving rate (2.7%/yr) and materials-using rate (2.8%/yr) of technical change for the period 1850–1919, but no significant effect of technical change on the demand for capital or other residual inputs. The materials-using bias was common to those industries which relied heavily upon raw materials derived from forests and mines. The authors attributed this pattern to the role of improved technology in the discovery of new sources of raw materials and in reducing transportation costs. Surprisingly, the commonly accepted pattern of capital-using, labor-saving technical change bias that has characterized the post World War II U.S. economy was rare among the 18 industries included in the study.

Wear (23) concluded that technical change reduced the demand for wood by about 1% per year in the Montana aggregate lumber and plywood industry over the period 1958–1978. However, he noted that average log diameters were declining over this period and that the time trend used as an index of the state of technology might have captured the effect of increasing overrun, thereby biasing the estimated coefficient of the time trend. He cautioned that if this was the case, technical change could actually have been wood-using over the study period.

The remaining two studies (5, 10) do provide an opportunity for meaningful comparisons. Both covered approximately the same time period and used similar models and estimation techniques. The results, however, were highly contradictory. Rao and Preston (10) estimated the average rate of technical progress in the Canadian industry to be approximately 2.0% per year. They also found a capital-saving and material-using bias to technical change but no significant effect on either labor or energy demand. Jorgenson and Fraumeni (5) did not report the average rate of technical change, but they indicated that it was capital-, labor-, and energy-using, and wood-saving for the U.S. industry.

Although there are some differences between the U.S. and Canadian industries, it is not apparent why the pattern of technical change should have been so different. It is worth noting that Jorgenson and Fraumeni estimated the biases of technical change for 36 U.S. industries, and found technical change to be labor-using for 31 industries. These results stand in stark contrast to those for the vast majority of other U.S. industries and must be viewed with some skepticism. The authors note that they obtained their results ". . . under strong simplifying assumptions . . . justified primarily by their usefulness in implementing production models that are uniform for all thirty-six industrial sectors of the U.S. economy" (Jorgenson and Fraumeni 1981, p. 45). It is possible that their attempt to achieve consistency across sectors forced an inappropriate structure on the production technology of the wood industry.

At the more disaggregated level, the sawmill and the veneer and plywood industries have been the focus of considerable analysis (Table 2). The sawmill industry in particular has drawn the attention of researchers in both the U.S. and Canada.

Sawmill

The sawmill industry is dominated by the production of softwood lumber and therefore the results which have been reported should be interpreted as being relevant principally to that segment of the industry. Studies of the sawmill industry which have included aggregate capital as a variable factor have all reported a capital-using technical change bias, and almost invariably a labor-using bias. However, when Merrifield and Haynes (13) disaggregated capital in the U.S. Pacific Northwest Eastside and Westside lumber industries into structures and equipment, they were unable to detect any significant effect of technical change on the demand for factors. Nor did they detect any significant changes in total factor productivity.

Of greatest interest to forest economists is the impact of technical change on the demand for wood or materials in the sawmill industry. *A priori* one might expect a wood-saving bias due to the adoption of modern equipment that is capable of increasing the yield per unit of log input. In fact, however, the results are split about evenly between wood-using and wood-saving biases, and a few studies report no significant bias in either direction. Moreover, the inconsistency of the results pertains to both the U.S. and Canadian industries, and even to specific regions within the two countries.

Five of the studies in Table 2 are of special interest. Abt (16) analyzed the production technology in two U.S. softwood (PNW and Southeast) and one hardwood (Appalachian) sawmilling industries. He did not report the rate of change in total factor productivity, but did report the effects of technical change on factor demands. He found technical change to exhibit a wood-saving bias in the Southeast, and a wood-using bias in the PNW softwood and Appalachian hardwood regions. Abt did not discuss these results except to note that in the PNW region this result was probably influenced by the effects of changing resource quality.

Martinello (12) reported a small negative trend (0.4%/yr) in total factor productivity in the aggregate Canadian sawmill industry from 1963 to 1981. Technical change was capital- and energy-using and wood- and labor-saving. However, in a later study Martinello (17) compared Coastal and Interior British Columbia sawmills. He found that technical change had no significant effect on the demand for wood in the Coastal industry, but that it reduced the demand for wood by 0.9% per year in the Interior industry. He, too, noted the decline in the size and quality of timber in the Interior region and cited Pearse (1980), who observed that this decline had stimulated investment in newer mills that were capable of processing large volumes of smaller logs, whereas the Coastal industry had not yet had to make the transition to a second-growth timber resource.

In one of the most detailed studies of the sawmill industry, Meil and Nautiyal (20) disaggregated the Canadian sawmill industry by region and by mill capacity as reflected in number of employees. They reported no significant increases in total factor productivity (TFP) over the study period (1968–1984) for any region or size class. Technical change had a labor-saving effect in all four regions, and for all but one size class. Similarly, with very few exceptions, the bias was material- and energy-using.

Finally, the study by Constantino and Haley (19) varies from the others in that the authors explicitly incorporated a quality-adjusted measure of wood input. The adjustment involved computing a weighted average of wood volume by log grade and a corresponding weighted average price. This approach removed the systematic bias that was incorporated into the time trend as a result of declining log quality over time. The authors reported small but similar rates of improvement in total factor productivity (approximately 0.6%/yr) for the U.S. PNW and the Canadian British Columbia sawmill industries from 1957 to 1981. They also found technical change to be wood- and labor-saving in the two industries.

Veneer and Plywood

The veneer and plywood industry has been the subject of two studies (Table 2). Merrifield and Haynes (13) reported a record of improvement in total factor productivity in the U.S. PNW Westside plywood industry but no significant trend in the Eastside industry. While the results were mixed for the technical change bias with respect to capital and energy, there was a labor-saving pattern for both industries. Martinello (17) also found a negative trend in TFP for the Canadian plywood industry, with technical change being capital-using and labor-saving. However, technical change either had no effect or was slightly wood-using in both the U.S. and Canadian PNW regions. Both studies noted the decline in wood quality over the study period and hypothesized that this decline might have masked some of the actual technical progress.

Pulp and Paper Industries

There have been seven analyses of the aggregate paper and allied products industries of the U.S. and of Canada (Table 2). Cain and Paterson's (4) work, which covered a unique time period, indicated that technical change was capital- and material-using in the U.S. industry during the latter half of the nineteenth and first part of the twentieth centuries. They attribute these results to the increasing dependence on cheaper Canadian sources of wood fiber. However, this explanation seems suspect because wood fiber was not the principal input during much of the period covered by the study and because Canadian imports, especially for newsprint, did not expand greatly until after 1915.

The capital-saving bias reported by Jorgenson and Fraumeni for the U.S. pulp and paper industry is even more unusual than their results for the aggregate solid wood products industry. They did, however, find that technical change had been energy-using, a result which is consistent with the findings of most other studies. However, in light of the unusual nature of their results, it is not known if any credence can be placed in the wood-using bias they report.

Chang's study (18) is also unusual because, while he used a multifactor model to derive the factor demand functions, he estimated only the demand for pulpwood and he did this in terms of an input-output coefficient. Over a relatively long time period (1950–1984), he was unable to detect any statistical evidence of any impact of technical change on the demand for wood per ton of woodpulp.

The remaining four studies are quite comparable; they cover similar periods and use similar models. Two report an energy-using bias for the Canadian industry (8, 10), and all but one (10) report a capital-using bias. No clear pattern emerges for labor; in two studies the technical change bias was labor-saving but in the other two it was insignificant. Two studies reported a wood-saving bias in the Canadian industry (8, 12), but one found no significant trend (10). Stier (14) reported a wood-using bias for the U.S. industry, but he did not include wastepaper as part of the wood input. The wood-using bias might, therefore, have included some of the systematic substitution of virgin fiber for wastepaper that was occurring over the study period.

Martinello (12) estimated that total factor productivity in the Canadian industry declined at the rate of 0.9% per year between 1963 and 1982. However, he also reported exceptionally large estimated returns to scale. It is likely that the data were unable to separate accurately the effects of changes in scale of production from those due to technical change.

DeBorger and Buongiorno (11) and Quicke et al. (24) examined the disaggregated paper industry (SIC 262) using very similar models and data. Both studies reported substantial rates of increase in total factor productivity, ranging from 2.0% to 4.0% per year depending upon the measure used. Both also found significant labor-saving and energy-using biases and Quicke et al. also reported a significant material-saving bias.

DeBorger and Buongiorno also analyzed the U.S. paperboard industry. They reported positive but much lower increases in total factor productivity (1.0%/yr) and they were unable to detect any significant factor biases in the pattern of technical change.

Third-Generation Studies

A major contribution of third-generation studies is their explicit inclusion of the dynamics of adjustment of quasi-fixed factors, such as capital. The three papers listed in Table 3 cover three separate industries.

Merrifield and Singleton (15) applied a fully dynamic capital adjustment model to the U.S. Pacific Northwest sawmill and veneer and plywood industries. They found both industries to be characterized by a capital-using bias. Technical change was labor-saving in the plywood industry and wood-saving in the sawmill industry. All of the estimated effects were numerically very small, indicating that technical

TABLE 3.

Results of third-generation technical change studies.

SIC Code[a]	Forest industry	Study[b]	Time period	Region	Technical change bias[c]
242	Sawmills & Planning Mills	15	1955–79	US–PNW	K^+,L^+,W^-
		21	1948–83	British Columbia Interior	L^-,E^+,M^+
243	Veneer & Plywood Mills	15	1955–79	US–PNW	K^+,L^-,W^+
26	Paper & Allied Products	22	1964–84	Canada	K^+,L^+,W^+,M^-

[a] SIC codes and industry titles follow the U.S. Department of Commerce system.
[b] Numbers refer to the studies listed in Table 1.
[c] K = capital, K_s = capital structures, K_e = capital equipment, L = labor, E = energy, W = wood, R = residual inputs, M = materials, + = factor i-using, − = factor i-saving, o = no significant bias.

change had had very little impact on factor demands in either industry. This result was consistent with Merrifield and Haynes' (1985) earlier study of the two industries which was based on a second-generation model.

Meil et al. (21) used an ad hoc lagged adjustment structure to account for the delay in adjustment of factor inputs in modeling the production structure of the British Columbia Interior softwood sawmill industry from 1948 to 1983. They reported technical change to be significantly labor-saving and materials-using in the Canadian sawmill industry. The effect on energy was not statistically significant. The labor-saving bias was also reported by Martinello (17) and Meil and Nautiyal (20), both of which used second-generation models to analyze the B.C. Interior sawmill industry. However, neither reported a wood-using bias.

Finally, Bernstein (22) used a variable profit function within a dynamic model of the Canadian pulp and paper industry. His model incorporated three variable factor inputs, a quasi-fixed capital input, and three outputs—newsprint, woodpulp, and other paper and paperboard—and permitted the industry to engage in markup pricing. Total factor productivity was estimated to have increased at the rate of 3.2% per year from 1961 to 1984. Technical change was labor-, capital-, and wood-using, and materials-saving, with materials defined to include also energy inputs. With the exception of the wood-using bias, these results contradict the factor biases estimated with second generation models (8, 10, 12).

Summary

Analyses based on simple two-factor (capital and labor) production models have largely confirmed the capital-using and labor-saving bias of technical change that is reported for much of the rest of the U.S. manufacturing sector in the post World War II period, and which is generally believed to hold for most forest products industries as well (Lange et al. 1990). However, the inclusion of additional factors and the use of more complex models of the production structure have substantially clouded the results. It is probably reasonable to conclude that technical change has largely been labor-saving and energy-using, but the extremely variable results for wood inputs provide little support for the hypothesis of wood-saving technical change.

EVALUATION OF RESEARCH

First-generation studies which are not based on flexible functional forms are inherently unable to differentiate between the effects of returns to scale, factor substitution and technical change. Consequently, the estimation of technical change effects can proceed only if rather restrictive maintained hypotheses are imposed on the structure of the production technology. The need to make these *a priori* assumptions severely limits the complexity of the functional forms used to represent the production technology and the ability of the data "to speak for themselves." In addition, most first-generation studies, including those based on flexible functional forms, have considered only capital and labor inputs. This ignores important interactions among omitted inputs such as energy and wood.

Second- and third-generation studies permit a far richer theoretical specification of production relationships. Specifically, they can incorporate any number of variable and quasi-fixed factors, they can incorporate scale, substitution, and technical change effects, and they permit the derivation of a system of internally consistent economic relationships. These are important features, especially in light of recent work which has demonstrated that third-generation factor demand models cannot be approximated with simpler first-generation models except in very specific circumstances (Watkins 1991). From an empirical standpoint, however, third-generation models do have limitations.

Models which incorporate substitution, scale, and technical change effects invariably involve a large number of parameters to be estimated. Most researchers have limited data, and data sets are often plagued by multicollinearity. For example, models which incorporate both technical change and returns to scale often have trouble differentiating between the two effects because the time trend that is typically used to represent technical change is usually highly correlated with output. As a practical limitation, therefore, it is often necessary to impose *a priori* restrictions on the empirical model, some of which are rather restrictive; e.g., linear homogeneity.

In addition, second- and third-generation studies are usually based on the dual cost or profit functions. Cost minimization and profit maximization are themselves important assumptions about the behavior of firms, assumptions which imply certain regularity conditions governing the parameters of the production technology. Some researchers either did not check whether these conditions were met or did not report their results, and some who did perform such checks reported questionable results [see, for example, Abt (1987) and Constantino and Haley (1988)]. Failure of the estimated parameters to meet the required conditions could arise either because the behavioral assumptions of cost minimization or profit maximization are not met or because the chosen functional form is not appropriate for the data. Unless such checks are made and reported, it is not possible to interpret the parameter estimates, such as the technical change biases, with much confidence.

While the development of flexible functional forms has facilitated more complex representations of the production technology, such forms do not guarantee meaningful results. All applied research requires theoretical and empirical tradeoffs. The commonly used translog functional form, for example, can yield unrestricted estimates of substitution elasticities, but at the cost of possibly violating global regularity conditions on the concavity of a production function or the convexity of a cost function. As substitution elasticities move away from unity and as cost shares become increasingly unbalanced, the regularity conditions are satisfied for a smaller range of relative prices for the translog (Guilkey et al. 1983, Thompson 1988, Considine 1989, Dowd et al. 1986). Hence, the different results reported in econometric studies may reflect differences due to the functional form used as well as differences in the underlying production parameters. A comparison of the properties of the most common flexible functional forms and their implications for the parameters of the production technology can be found in Fuss and McFadden (1978).

Many studies involve only the estimation of the derived factor demand or share equations. Since the parent cost or profit function also contains information not in the derived equations, it would be desirable whenever possible to estimate the parameters of the full equation system. This can be done by estimating simultaneously the parent function and all but one of the factor share equations as a multivariate system. This procedure is becoming more common as computer technology and software improve and become more widely available.

Perhaps the most severe theoretical limitation of all the studies examined is their use of a time trend as a proxy for the state of technology. There is no reason to suppose that technical change occurs in a smooth, orderly manner; indeed, the literature on diffusion of technology and technological forecasting suggests that it often occurs in spurts (Sahal 1981, Martino 1983). The linear time trend is also often highly correlated with output or prices. Thus, its use not only implies an incorrect measure of changes in the state of technology; it also frequently introduces statistical problems into the model and forces the researcher to simplify the model structure by making *a priori* assumptions (Peterson and Hayami 1977). The difficulty lies not in any deficiency of economic theory but rather in the perennial bane of empirical work, insufficient data to differentiate among theories.

IMPLICATIONS FOR FUTURE RESEARCH

It is surprising that most of the studies summarized in Table 1 which include wood inputs have found that technical change has had a negligible effect on wood requirements; i.e., that technical change is basically wood-neutral. This finding is at odds with evidence of major wood-saving technologies in the forest industries; e.g., Anderson (1987), Haynes (1990), Haygreen et al. (1986), Rosenberg et al. (1990).

Ideally, expansion of the set of factor inputs to include a more detailed breakdown, such as softwood vs. hardwood or pulpwood vs. wastepaper, and to incorporate changes in the quality of inputs, might yield more specific and consistent results. However, while such a detailed representation of the production process is conceptually feasible, it would likely not be empirically tractable. As the number of variables expands, degrees of freedom are quickly exhausted and multicollinearity among explanatory variables becomes a virtual certainty.

To increase the possibility of obtaining meaningful results from the econometric approach, several strategies might be considered. First, the state of technology is not captured very well by a time trend. Rather, it should be represented in a way that more accurately reflects both the actual productive capability as well as the rate at which it changes over time. Examples of technological variables which might be used would be the type of headrig in a sawmill or the horsepower rating of certain machinery such as motors, or rate of throughput (speed × width) of paper machines (Steele and Stier 1991) or wood panel presses. Clearly, not all industries or production processes will lend themselves to such simple description, but for those which do the econometric approach might be usefully employed.

Technological forecasters have also developed several approaches for representing the state of technology based on the function the technology performs and key technical parameters. For example, scoring models, constrained scoring models, and tradeoff surfaces have all been used to obtain indexes of technical change over time when several identifiable technical characteristics were important (Alexander and Nelson 1973, Dodson 1970, Gordon and Munson 1981). These characteristics might include speed, weight, energy consumption, delay times, precision, or accuracy.

A second avenue to explore would be the use of time series data for an individual mill in conjunction with an index of the state of technology such as those described above. At the individual mill level the problem of compensating variation that can occur at the aggregate industry level would be less likely.

A third strategy which might prove useful is the use of cross-section data. All of the studies in Table 1 were based on time series data. Because of the tendency of variables to "drift" over time, time series often do not contain the range of variation that cross-sectional data sets exhibit. If a suitable index of the state of technology can be formulated, the cross-sectional approach might prove very useful (Peterson and Hayami 1977).

Finally, the three approaches could be combined by using panel data. This is the approach Cardellichio (1989) employed to examine the production behavior of the Washington sawmill industry for the period 1972–1984. He used unit log use, which is an input-output ratio and is the inverse of the overrun ratio, as the dependent variable. The state of technology was represented by two mill specific variables, mill age and type of headrig. To control for changes in wood quality, he included dependent variables representing species and type of wood sawn (old growth, utility, or dead), as well as geographic region and mill capacity. The estimated coefficient for mill age was negative and highly significant, indicating that, other things equal, newer mills could saw more lumber from a given volume of logs than older mills. He also found that mills with circular saws used more log input per unit of lumber output, and mills with chipping headrigs less, than did those with band saws. Analysis of residuals indicated that the mean error for each year was not zero. Cardellichio then reestimated the model, once with a simple linear time trend and a second time with dummy variables for different time periods. Both models fit the data better than the original, and the latter revealed discrete downward shifts in the input-output ratio in 1978 and 1982. However, Cardellichio was unable to provide an explanation for the shifts and the inclusion of time in both models had the effect of making relative price of wood an insignificant variable.

Models which incorporate a hybrid strategy that relies on both the econometric and index approaches, which use panel data and which explicitly incorporate technical change without resorting to a simple time trend might be the most promising for future research. Baltagi and Griffin (1988) introduced such an approach and were reasonably successful in demonstrating nonlinear changes in total factor productivity and biased technical change for electrical utilities in the United States. Their approach would be worth exploring in the forest industries.

Given the heterogeneity of the raw material "wood," it is unlikely that the econometric approach alone will ever be able to capture adequately the process of technical change in the forest industries. Another approach which deserves further attention is the use of simulation to model the effects of technical change on the demand for factors. Spelter and Sleet (1989) constructed a simulation model for the manufacture of softwood plywood in the U.S. They used the model to estimate the cost of production with individual and combined changes in technology and were able to demonstrate significant savings in wood and labor costs resulting from several innovations.

A substantial body of literature has accumulated on the econometric approach to estimating the rate and direction of technical change in the forestry sector. The record of this research, in terms of meaningful and consistent results, is not very good. Meaningful progress is not likely to be made until there is better development of conceptual and empirical measures of the state of technology which can be incorporated into the econometric approach.

LITERATURE CITED

ABRAHAMOVITZ, M. 1956. Resource and output trends in the United States since 1870. Am. Econ. Rev. 46(2):5–23.

ABT, R.C. 1987. An analysis of regional factor demand in the U.S. lumber industry. For. Sci. 33(1):164–173.

ANDERSON, W.C. 1987. Technical changes that solved the southern pine lumber industry's small-log problem. For. Prod. J. 37(6):41–45.

ALEXANDER, A.J., and J.R. NELSON. 1973. Measuring technological change: Aircraft turbine engines. Tech. For. Soc. Change 5:189–203.

BALTAGI, B.H., and J.M. GRIFFIN. 1988. A general index of technical change. J. Polit. Econ. 96(1):20–41.

BENGSTON, D.N. 1984. Economic impacts of structural particleboard use. For. Sci. 30(3):685–697.

BENGSTON, D.N. 1985. Economic evaluation of agricultural research. Eval. Rev. 9(3):243–262.

BENGSTON, D.N., and H.M. GREGERSEN. 1991. Technical change in the forest-based sector. J. Bus. Admin. 20: (In press).

BERNDT, E.R., and M.S. KHALED. 1979. Parametric productivity measurement and choice among flexible functional forms. J. Polit. Econ. 87(6):1220–1245.

BERNSTEIN, J.I. 1989. Taxes, production and adjustment in the Canadian pulp and paper industry. For. Canada, Econ. Branch Work. Pap. Ottawa. 36 p.

BINSWANGER, H.P. 1978. Induced technical change: Evolution of thought. P. 13–43 *in* Induced innovation: Technology, institutions, and development, Binswanger, H.P., and V.W. Ruttan (eds.). The Johns Hopkins University Press, Baltimore, MD. 423 p.

BLACKORBY, C., and R.R. RUSSELL. 1989. Will the real elasticity of substitution please stand up? (A comparison of the Allen/Uzawa and Morishima elasticities) Am. Econ. Rev. 79(4):882–888.

BUONGIORNO, J., and R.A. OLIVEIRA. 1977. Growth of the particle board share of production of wood-based panels in industrialized countries. For. Sci. 7(2):383–391.

CAIN, L.P., and D.G. PATERSON. 1981. Factor biases and technical change in manufacturing: The American system, 1850–1919. J. Econ. Hist. 41(2):341–360.

CARDELLICHIO, A. 1989. Determinants of log-to-lumber conversion efficiency: A Washington case study. For. Sci. 35(2):437–452.

CHAMBERS, R. 1982. Relevance of duality theory to the practicing agricultural economist: Discussion. West. J. Agric. Econ. 7(2):373–378.

CHANG, S.J. 1988. An econometric study of the U.S. pulp industry and its technological progress. P. 205–208 *in* Proc. 1988 South. For. Econ. Workshop, Abt, R.C. (ed.). 302 p.

CHRISTENSEN, L.R., D.W. JORGENSON, and L.J. LAU. 1973. Transcendental logarithmic production frontiers. Rev. Econ. Statis. 55(1):28–45.

COHEN, A.J. 1984. Technological change as historical process: The case of the U.S. pulp and paper industry, 1915–1940. J. Econ. Hist. 44:775–799.

COHEN, A.J. 1987. Factor substitution and induced innovation in North American kraft pulping: 1914–1940. Explor. Econ. Hist. 24:197–217.

CONSIDINE, T.J. 1989. Estimating the demand for energy and natural resource inputs: trade-offs in global properties. Appl. Econ. 21(7):931–945.

CONSTANTINO, L.F., and D. HALEY. 1988. Wood quality and the input and output choices of sawmilling producers for the British Columbia coast and the United States Pacific Northwest, west side. Can. J. For. Res. 18(2):202–208.

CONSTANTINO, L.F., and D. HALEY. 1989. A comparative analysis of sawmilling productivity on the British Columbia coast and in the U.S. Douglas-fir region: 1957–1982. For. Prod. J. 39(4):57–61.

CONSTANTINO, L., and G. TOWNSEND. 1989. Modeling operating rate decisions in the Canadian forest industries. West. J. Agric. Econ. 14(2):268–280.

DE BORGER, B., and J. BUONGIORNO. 1985. Productivity growth in the paper and paperboard industries: A variable cost function approach. Can. J. For. Res. 15(6):1013–1020.

DIEWERT, W.E. 1971. An application of the Shepard Duality Theorem: A generalized Leontief production function. J. Polit. Econ. 79(3):481–507.

DODSON, E.N. 1970. A general approach to measurement of the state of the art and technological advance. Tech. For. Soc. Change 1:391–408.

DOWD, J., R. RYE, and R. KAUFMANN. 1986. Do flexible functional forms generate accurate elasticities? P. 456–460 *in* The changing world energy economy, papers and Proc. of the 8th Annual North Am. Conf., Internat. Assoc. of Energy Econ. MIT Press, Cambridge, MA.

DUKE, J., and C. HUFFSTUTLER. 1977. Productivity in sawmills increases as labor input declines substantially. Mon. Labor Rev. 100(4):33–37.

FARRIS, H. 1978. The veneer and plywood industry: Above average productivity gains. Mon. Labor Rev. 101(9):26–30.

FRANK, D.L., A. GHEBREMICHAEL, T.H. OUM, and M.W. TRETHEWAY. 1988. Economic performance of the Canadian pulp and paper industry: 1963–1982. Univ. British Columbia, For. Econ. & Policy Anal. Res. Work. Pap. No. 107. Vancouver. 85 p.

FUSS, M.A., and D.L. MCFADDEN. 1978. Production economics: A dual approach to theory and application. Amsterdam: North Holland. 482 p.

GHEBREMICHAEL, A., D.G. ROBERTS, and M. TRETHEWAY. 1990. Productivity in the Canadian lumber industry: An inter-regional comparison. For. Can. Inf. Rep. O-X-411. 73 p.

GLOBERMAN, S. 1976. New technology adoption in the Canadian paper industry. I.O. Rev. 4:5–12.

GORDON, T.J., and T.R. MUNSON. 1981. A proposed convention for measuring the state of the art of products and processes. Tech. For. Soc. Change 20:1–26.

GREBER, B., and D. WHITE. 1982. Technical change and productivity growth in the lumber and wood products industry. For. Sci. 28(1):135–147.

GUILKEY, D.K., C.A. KNOX LOVELL, and R.C. SICKLES. 1983. A comparison of the performance of three flexible functional forms. Inter. Econ. Rev. 24(3):591–616.

GUTTMAN, J.M. 1978. Interest groups and the demand for agricultural research. J. Polit. Econ. 86(3):4676–484.

HAYGREEN, J., H. GREGERSEN, I. HOLLAND and R. STONE. 1986. The economic impact of timber utilization research. For. Prod. J. 36(2):12–20.

HAYNES, R.W. 1990. An analysis of the timber situation in the United States: 1989–2040. USDA For. Serv. GTR-RM-199. 268 p.

HERRICK, O.W. 1982. Estimating benefits from whole-tree chipping as a logging innovation in northern forests. For. Prod. J. 32(11/12):57–60.

HJELM, J. 1991. The chain saw in Swedish forestry. Tech. Forecast. Soc. Change 39(1–2):221–231.

JORGENSON, D., and B. FRAUMENI. 1981. Relative prices and technical change. P. 1–47 *in* Modelling and measuring natural resource substitution, Berndt, E.R., and B.C. Field (eds.). MIT Press, Cambridge, MA. 314 p.

KAISER, H.F. 1971. Productivity gains in forest products industries. For. Prod. J. 21(5):14–16.

LANGE, W.J., K.E. SKOG, A.J. PLANTINGA, and H. SPELTER. 1990. Regional projections of employment and wages in the softwood lumber and plywood industries. P. 265–269 *in* Forestry on the frontier. Proc. 1989 SAF Nat. Conv. Soc. Am. For., Bethesda, MD.

LEEFERS, L.A. 1981. Product innovation and diffusion in the wood-based panel industry. Ph.D. thesis, Michigan State Univ., East Lansing, MI. 212 p.

LINK, A.N. 1983. Alternative sources of technology: An analysis of induced innovations. Manage. Decision Econ. 4(1):40–43.

MCGOVERN, J.N. 1984. Development and mill transfer of the FPL semichemical pulping process. Tappi 67(6):30–34.

MANNING, G.H., and G. THORNBURN. 1971. Capital deepening and technological change: The Canadian pulp and paper industry, 1940–1960. Can. J. For. Res. 1(3):159–166.

MARTINELLO, F. 1984. Substitution, technical change, and returns to outlay in the B.C. wood products industry. Dept. of Econ., Carleton Univ. Work. Pap. No. 84-11. 21 p.

MARTINELLO, F. 1985. Factor substitution, technical change, and returns to scale in Canadian forest industries. Can. J. For. Res. 15(6):1116–1124.

MARTINELLO, F. 1987. Substitution, technical change and returns to scale in British Columbian wood products industries. Appl. Econ. 19(4):483–496.

MARTINO, J.P. 1983. Technological forecasting for decision making. Ed. 2. North-Holland, New York. 385 p.

MEIL, J.K., and J.C. NAUTIYAL. 1988. An intraregional economic analysis of production structure and factor demand in major Canadian softwood lumber producing regions. Can. J. For. Res. 18(8):1036–1048.

MEIL, J.K., B.K. SINGH, and J.C. NAUTIYAL. 1988. Short-run actual and least-cost productivities of variable inputs for the British Columbia Interior softwood lumber industry. For. Sci. 34(1):88–101.

MERRIFIELD, D.E., and R.W. HAYNES. 1985. A cost analysis of the lumber and plywood industries in two Pacific Northwest sub-regions. Annals Reg. Sci. 19(3):16–33.

MERRIFIELD, D.E., AND W.R. SINGLETON. 1986. A dynamic cost and factor demand analysis for the Pacific Northwest lumber and plywood industries. For. Sci. 32(1):220–233.

MONTREY, H., and J.M. UTTERBACK. 1990. Current status and future of structural panels in the wood products industry. Tech. Forecast. Soc. Change 38:15–35.

MORONEY, J.R. 1968. Technological progress, factor proportions, and the relative share of capital in American manufacturing, 1942–1957. West. Econ. J. 6(5):359–374.

NAUTIYAL, J.C., and B.K. SINGH. 1986. Long-term productivity and factor demand in the Canadian pulp and paper industry. Can. J. Agric. Econ. 34(1):21–44.

NEWMAN, D.H. 1986a. Changes in southern softwood productivity: A modified production function analysis. Southeast. Center For. Econ. Res. Work. Pap. No. 29. Research Triangle, NC. 62 p.

NEWMAN, D.H. 1986b. Measurement of technological change in softwood timber management: A Southern United States case study. P. 13–22 *in* Valuation of forestry research, Proc. IUFRO Working Party S4.05-05 meeting. 65 p.

NEWMAN, D.H. 1990a. Changes in southern softwood productivity: A modified production function analysis. Unpubl. manuscript. 29 p.

NEWMAN, D.H. 1990b. Shifting southern softwood stumpage supply: Implications for welfare from technical change. For. Sci. 36(3):705–718.

OUM, T.H., M.W. TRETHEWAY, and Y. ZHANG. 1990. Productivity measurement for the pulp and paper industry with adjustment for capacity utilization: A comparison of Canada, Sweden and the U.S. Univ. British Columbia, For. Econ. Pol. Anal. Res. Work. Pap. No. 143. 72 p.

PEARSE, P.H. 1980. The forest industries of British Columbia: B.C. Tel Series in Bus. Econ. No. 1. B.C. Telephone Co., Vancouver.

PETERSON, W., and Y. HAYAMI. 1977. Technical change in agriculture. P. 497–540 *in* A survey of agricultural economics literature. Vol. I. L.R. Martin (ed.). Univ. Minn. Press, St. Paul.

QUICKE, H.E., J.P. CAULFIELD, and P.A. DUFFY. 1990. The production structure of the U.S. paper industry. For. Prod. J. 49(9):44–48.

RAO, P.S. 1981. Factor prices and labour productivity in the Canadian manufacturing industries. Empir. Econ. 6(4):187–202.

RAO, P.S., and R.S. PRESTON. 1984. Inter-factor substitution, economies of scale and technical change: Evidence from Canadian industries. Empir. Econ. 9(2):87–111.

RISBRUDT, C.D. 1979. Past and future technological change in the U.S. forest industries. Ph.D. diss., Michigan State University. 166 p.

ROBINSON, V.L. 1975. An estimate of technological progress in the lumber and wood-products industry. For. Sci. 21(2):149–154.

ROBSON, M., J. TOWNSEND, and K. PAVITT. 1988. Sectoral patterns of production and use of innovations in the UK: 1945–1983.

ROSENBERG, N. 1972. Technology and American economic growth. Harper Torchbooks, New York. 211 p.

ROSENBERG, N. 1973. Innovative responses to materials shortages. Am. Econ. Rev. 63(2):111–118.

ROSENBERG, N., P. INCE, K. SKOG, and A. PLANTINGA. 1990. Understanding the adoption of new technology in the forest products industry. For. Prod. J. 40(10):15–22.

RUTTAN, V.W. 1982. Agricultural research policy. University of Minnesota Press, Minneapolis. 369 p.

RUTTAN, V.W. 1956. The contribution of technological progress to farm output: 1950–75. Rev. Econ. Statis. 38(1):61–69.

RUTTAN, V.W., and J.C. CALLAHAN. 1962. Resource inputs and output growth: Comparisons between agriculture and forestry. For. Sci. 8(1):68–82.

SAHAL, D. 1981. Patterns of technological innovation. Addison-Wesley, Reading, MA. 381 p.

SANDOE, M., and M. WAYMAN. 1977. Productivity of capital and labor in the Canadian forest products industry, 1965 to 1972. Can. J. For. Res. 7(1):85–93.

SCHERER, F.M. 1982. Inter-industry technology flows in the United States. Res. Pol. 11(2):227–245.

SCHMOOKLER, J. 1952. The changing efficiency of the American economy, 1869–1938. Rev. Econ. Statis. 34(3):214–231.

SELDON, B.J. 1987a. Economic evaluation of forestry research: Synthesis and methodology. P. 161–176 *In* Evaluating agricultural productivity. Minn. Agric. Exp. Stn. Misc. Publ. 52–1987. 207 p.

SELDON, B.J. 1987b. A nonresidual estimation of welfare gains from research: The case of public R&D in a forest products industry. South. J. Econ. 54(1):64–80.

SELDON, B.J., and W.F. HYDE. 1991a. An evaluation of public research in three forest products industries. For. Sci. 37(2):669–687.

SELDON, B.J., and W.F. HYDE. 1991b. Welfare gains from wood preservatives research. J. Agric. Econ. Res. 43(1):22–29.

SELDON, B.J., and W.F. HYDE. 1991c. An evaluation of public research in three forest products industries. For. Sci. 37(2):669–687.

SELDON, B.J., and D. H. NEWMAN. 1987. Marginal productivity of public research in the softwood plywood industry: A dual approach. For. Sci. 33(4):872–888.

SHERIF, F. 1983. Derived demand of factors of production in the pulp and paper industry. For. Prod. J. 33(1):45–49.

SINGH, B.K., and J.C. NAUTIYAL. 1986. A comparison of observed and long-run productivity of and demand for inputs in the Canadian lumber industry. Can. J. For. Res. 16(3):443–455.

SKOG, K., and R. HAYNES. 1987. The stumpage market impact of timber utilization research. For. Prod. J. 37(6):54–60.

SOLOW, R.M. 1957. Technological change and the aggregate production function. Rev. Econ. Statis. 39(4):312–320.

SPELTER, H. 1985. A product diffusion approach to modeling softwood lumber demand. For. Sci. 31(3):685–700.

SPELTER, H., and G. SLEET. 1989. Potential reductions in plywood manufacturing costs resulting from improved technology. For. Prod. J. 39(1):8–15.

STEELE, T.W., and J.C. STIER. 1991. Capacity expansion and strategic behavior in the North American newsprint industry. P. 118–124 *in* Proc. 1991 Symp. on systems analysis in forest resources. USDA For. Serv. GTR-SE-74. 423 p.

STIER, J. 1980a. Estimating the production technology of the U.S. forest products industries. For. Sci. 26(3):471–482.

STIER, J. 1980b. Technological adaptation to resource scarcity in the U.S. lumber industry. West. J. Agric. Econ. 5(2):165–175.

STIER, J.C. 1982. Changes in the technology of harvesting timber in the United States: Some implications for labour. Agric. Syst. 9(4):255–266.

STIER, J.C. 1983a. Technical change and productivity growth in the lumber and wood products industry: Comment. For. Sci. 29(4):842–844.

STIER, J.C. 1983b. Technological substitution in the United States pulp and paper industry: The sulfate pulping process. Tech. Forecast. Soc. Change 23(3):237–245.

STIER, J.C. 1985. Implications of factor substitution, economies of scale, and technological change for the cost of production in the United States pulp and paper industry. For. Sci. 31(4):803–812.

STIER, J.C. 1990. Economic efficiency of forest tree improvement programs in the North Central Region. Eval. Rev. 14(3):227–246.

THIRTLE, C.G., and V.W. RUTTAN. 1987. The role of demand and supply in the generation and diffusion of technical change. Harwood Academic Publishers, New York. 173 p.

THOMPSON, G.D. 1988. Choice of flexible functional forms: Review and appraisal. West. J. Agric. Econ. 13(2):169–183.

VARIAN, H. 1978. Microeconomic analysis. W.W. Norton, New York. 284 p.

WALLACE, T.D., and D.H. NEWMAN. 1986. Measurement of ownership effects on forest productivity in North Carolina from 1974 to 1984. Can. J. For. Res. 16(4):733–738.

WATKINS, G.C. 1991. Short- and long-term equilibria: Relationships between first and third generation dynamic factor demand models. Energy Econ. 13(1):2–9.

WEAR, D.N. 1989. Structural change and factor demand in Montana's solid wood products industries. Can. J. For. Res. 19(5):645–650.

WESTGATE, R.A. 1986. The economics of containerized forest tree seedling research in the United States. Can. J. For. Res. 16(5):1007–1012.

XU, Z., D.N. BENGSTON, H.M. GREGERSEN, and A.L. LUNDGREN. 1990. Regional impacts of technical change: The case of structural particleboard in the United States. Unpubl. manuscript. 25 p.

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