Technological Adaptation to Resource Scarcity in the U.S. Lumber Industry

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This paper provides an econometric investigation of the role of a renewable natural resource, sawlogs, in the production of lumber over the period 1950-1974. The economic scarcity of sawlogs is confirmed. Within a given production technology, the potential for substitution among capital, labor and sawlog inputs is greatly restricted but not impossible. Technological change has been strongly labor-saving but has had a negligible effect on wood requirements. Consequently, the real price of lumber has risen, stimulating development of substitute wood products. Continued decline of the industry is anticipated.

In their classic study of natural resource supplies, *Scarcity and Growth*, Barnett and Morse argued that there was little empirical evidence to support the hypothesis of increasing scarcity of raw materials in the United States. Taking increases in unit costs and relative prices as indications of growing scarcity, the authors concluded that over the period from 1870 to 1957, only one resource commodity, sawlogs[1], exhibited clear upward trends in both costs and prices.

Recently, Manthy [1977] extended the analysis of relative price trends with data from 1957 to 1973 and confirmed that only the forestry sector was characterized by scarcity. Manthy reported that the aggregate real price index for forest products had risen at an average annual rate of 1.39% since 1870, and was able to demonstrate that this trend was due primarily to the rapid rate of increase in the price of sawlogs (2.12% per year).[2]

Sawlogs constitute as much as 75% of the variable costs of lumber production [Sandwell Management Consultants, Ltd.]. Consequently, the growing scarcity of sawlogs could be expected to generate a strong economic incentive to reduce dependency upon log inputs through, e.g., substitution of more abundant factors and technological change. Barnett and Morse [pp. 131-137, 197-198] conjectured that the occurrence of both mechanisms had probably caused the capital-labor ratio in the lumber industry to increase, but they were unable to test their supposition.

This paper presents an empirical analysis of the nature and extent of factor substitution and technological innovation in the U.S. lumber industry over the period 1950-1974. An industry cost function is estimated and

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[1] Sawlogs are logs of suitable size and quality for producing lumber. High quality sawlogs which may be suitable for the production of veneer are referred to as veneer logs.

[2] The simple indexes employed by Barnett and Morse, and Manthy have significant limitations as indicators of natural resource scarcity (Smith, 1978, 1979). However, they are readily understood, widely accepted, and have greatly influenced public policy, especially in forestry [Manthy, 1977].

the parameters used to determine the impacts that substitution and innovation have had on the demand for factors and the unit cost of production. The results indicate the occurrence of capital-using technological change which enabled the labor force to be reduced by almost 50% while output remained virtually constant. However, the production technology has not proved sufficiently flexible to mitigate completely the effects of resource scarcity. The real price of lumber has continued to rise, stimulating further substitution in the product market.

Structure of the U.S. Lumber Industry

The lumber industry is taken to be all firms falling within the U.S. Department of Commerce Standard Industrial Classification (SIC) 242, which includes three subindustries: sawmills and planing mills (SIC 2421), hardwood dimension and flooring (SIC 2426), and special product mills (SIC 2429). Over the period under study, the latter two subindustries combined have accounted for about 10% of total value added and employment in the lumber industry [U.S. Department of Commerce]. Therefore, references to the aggregate industry are primarily to the sawmills and planing mills subindustry.

Between 1951 and 1972 the number of sawmills declined from almost 20,000 to 9,448 [U.S. Department of Commerce]. Nevertheless, the industry is generally considered to be highly competitive [Gregory; Rinfret Boston and Associates; U.S. Council on Wage and Price Stability]. Approximately 9,000 firms were in production in 1972, with the top twenty firms accounting for less than one-third of total shipments [U.S. Department of Commerce, 1975].

Almost 50% of the total U.S. timber harvest is sawn into lumber. Softwood species constitute the largest proportion (80%) of the harvest, with 71% of all softwood lumber produced in western states, principally California, Oregon, and Washington [Phelps]. Many firms are dependent on public forest lands for a portion of their sawtimber needs, and often purchase timber in the form of standing trees, i.e., stumpage, rather than as sawlogs. However, for the major sawtimber species stumpage and sawlog price movements are highly correlated [Phelps], so that either can serve as an indicator of relative price change.

Change in the quantities and prices of output and inputs over the 25 year period are shown in Table 1. Percentage change was calculated by dividing the mean value for the last three years in a data series by the mean value for the first three years, and subtracting unity. This procedure dampens some of the annual variation and yields a better indication of the general trend. Most notable in Table 1 is the stability of total output. Although per capita lumber consumption declined over the period by almost 30% [Phelps], total domestic production fell by just 2%.

Log input declined by considerably more

TABLE 1. Percentage Change in Outputs, Inputs and Prices in the U.S. Lumber Industry, 1950-1974.

	Total Percentage Change In:[a]	
Variable	Quantity	Nominal Price
Lumber Output	− 2%	+106%
Labor	−49%	+189%
Capital	+44%	+ 77%
Sawlogs	− 5%	+112%

[a]Sources and methods of derivation of price and quantity data are discussed in the text.

than output, which suggests that technological advancement was occurring. However, the largest saving was in labor requirement which was cut by half. Since real capital stock rose, it might be hypothesized that technological change resulted in the substitution over time of capital for scarce labor and wood. This hypothesis can be tested statistically if estimates of the technological change biases and the elasticities of factor substitution are available.

The application of duality principles to econometric theory enables the factor substitution elasticities and technological change biases to be related directly to certain parameters of the cost function [Shephard]; therefore, hypotheses about the former are logically equivalent to statements about the form of the cost function. Until recently, however, econometric theory had not advanced sufficiently to permit all the relevant parameters to be estimated freely and it was necessary to impose *a priori* restrictions on either the substitution elasticities or the factor biases in order to estimate cost or production functions (Diamond and McFadden). The recent introduction of flexible functional forms, such as the transcendental logarithmic or translog[3], enables simultaneous estimation of all cost function parameters necessary to test directly hypotheses about the substitution elasticities and technological change biases.

The Model

Under the assumptions of constant returns to scale and a constant rate of technological progress, the translog cost function with N factor inputs can be written as

$$(1)\quad AC = \exp(\alpha_0+\beta_T+\sum_i \beta_i \ell n\ P_i+\tfrac{1}{2}\gamma_{TT}T^2$$
$$+\tfrac{1}{2}\sum_i\sum_j \gamma_{ij}\ell n\ P_i \ell n\ P_j+\sum_i \gamma_{Ti}T\ \ell n\ P_i)$$
$$i,\ j = 1,\ 2,\ \ldots,\ N$$

where AC is average cost of output, P_i are factor prices and T represents the state of technology for which time is taken as a proxy. If (1) represents the minimum unit cost of producing any given level of output, Shephard's Lemma [Shephard] can be invoked to obtain the derived factor demand functions by differentiating the cost function with respect to factor prices

$$(2)\quad \frac{\partial\, AC}{\partial\, P_i} = X_i\,(P_j,\ T)\quad j = 1,\ 2,\ \ldots,\ N$$

where X_i is the cost minimizing demand for the ith factor. In logarithmic form, Shephard's Lemma yields the factor cost shares, S_i,

$$(3)\qquad \frac{\partial\ \ell n\ AC}{\partial\ \ell n\ P_i} = \frac{P_i\ X_i}{\sum_i P_i\ X_i} = S_i\ .$$

A well behaved cost function is twice differentiable and homogeneous of degree one in factor prices. These properties imply the following relationships among the parameters:

$$(4)\qquad \beta_{ij} = \beta_{ji}$$

$$(5)\qquad \sum_i \beta_i = 1$$

$$(6)\quad \sum_i \gamma_{Ti} = \sum_i \gamma_{ij} = \sum_j \gamma_{ij} = \sum_i\sum_j \gamma_{ij} = 0\ .$$

With the symmetry condition (4) imposed, the cost shares for the translog function (1) are given by

$$(7)\qquad S_i = \beta_i+\sum_j \gamma_{ij}\ell n\ P_j+\gamma_{Ti}T$$

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[3] The translog function was introduced by Christensen *et al.* It has been used extensively in recent years to model cost, production and profit functions. Details of the function's properties and examples of applications can be found in Berndt and Wood, Brown *et al.*, Caves and Christensen, Christensen and Greene, Humphrey and Moroney, Pindyck, and Wills.

A major objective is to obtain estimates of the Allen partial elasticities of substitution between factors [Allen], and the technological change biases. Uzawa demonstrated that the former can be obtained from the cost function according to the formula

$$\text{(8)} \qquad \sigma_{ij} = \frac{(C)\left(\frac{\partial^2 C}{\partial P_i\ \partial P_j}\right)}{\left(\frac{\partial C}{\partial P_i}\right)\left(\frac{\partial C}{\partial P_j}\right)} .$$

The symmetry condition (4) implies that $\sigma_{ij} = \sigma_{ji}$. For the translog cost function, equation (8) takes the form

$$\text{(9)} \quad \sigma_{ij} = (\gamma_{ij}+S_i+S_j)/S_iS_j \quad i \neq j.$$

The traditional Hicksian [Hicks] definition of technological change bias is adequate for a two-factor production model, but does not generalize well to the multifactor case. Binswanger has suggested an alternative measure which provides a single measure of the bias for each factor, and which is related directly to the familiar Hicksian definition. The bias for factor i (B_i) is given by

$$\text{(10)} \qquad B_i = \frac{\partial S_i^*}{\partial T} \frac{1}{S_i^*}$$

where S_i^* is the cost share given constant relative factor prices. The share equations (7) provide the information necessary to compute the biases, viz.,

$$\text{(11)} \qquad B_i = \frac{\gamma_{Ti}}{S_i^*} .$$

Technological change is said to be factor i− using, i− neutral or i− saving according to whether B_i is positive, zero or negative.

Estimates of the parameters of the translog cost function (1) could be obtained using ordinary least squares regression. However, additional information is available from the share equations (7). Assuming that the disturbance terms of the cost and share equations exhibit contemporaneous correlation only, the method of seemingly unrelated regression [Zellner] is appropriate. To avoid singularity of the disturbance covariance matrix arising from the linear homogeneity property, one share equation can be deleted and the iterative Zellner estimation procedure used. Kmenta and Gilbert and Dhrymes have shown that if the iteration process is continued until convergence is achieved, maximum likelihood estimates are obtained. This procedure was employed to obtain estimates of the parameters of a translog cost function defined for three factors — capital (K), labor (L), and sawlogs (W) — for the U.S. lumber industry.

Data

Time series data on domestic lumber production, log inputs, and the price index for lumber are published by the U.S. Forest Service [U.S. Department of Agriculture, Phelps]. Manthy [1978] reported an all-species sawlog price series for the years 1950-73. The price for 1974 was calculated by linking the price of sawlogs to the wholesale price index for softwood lumber. This ratio, which was very stable for the years 1970-73 ($\bar{x}$ = .4658; s.d. = .0025), was assumed to hold for 1974 as well.

The wage rate was calculated by dividing total payroll by aggregate man-hours of employment, with nonproduction workers assumed to work 2,000 hours annually [U.S. Department of Commerce].

Capital services are inherently difficult to measure. It was assumed that service flow is proportional to capital stock. The U.S. Department of Labor [1979] recently constructed constant dollar capital stocks series based upon the actual physical lives of equipment and structures. These estimates were used as a measure of capital input. The return to capital was computed by dividing gross quasi-rent, i.e., value added minus payroll, by the capital stock.

Results and Discussion

Estimates of all parameters of the translog cost function are presented in Table 2. Ten of the parameters were estimated directly; the remaining five were obtained from the homogeneity restrictions (5) and (6).

A well behaved cost function is monotonic and concave in factor prices. These conditions were checked for every observation using the parameter estimates.[4] The concavity condition was violated at two observations. Although the estimated function appears generally to fit the requirements of a cost function over the range of data, the results must be interpreted with some caution.

The estimated cross product terms $\hat{\gamma}_{ij}$ and the mean share values were substituted into equation (9) to obtain point estimates of the mean partial elasticities of factor substitution. The results are[5]

$$\begin{array}{llllll} \hat{\sigma}_{KL}: & 0.194 & \hat{\sigma}_{KW}: & 0.176 & \hat{\sigma}_{LW}: & 0.360 \\ & (0.058) & & (0.064) & & (0.064) \end{array}$$

All three estimates are significantly less than unity but greater than zero at the 95% confidence level; thus, neither the Cobb-Douglas nor the fixed coefficients production technology is consistent with the data. Within a static production technology, substitution possibilities are greatest between labor and wood. There is some evidence that this flexibility remains. Recent studies of the efficiency of mill operations have revealed that allocation of additional labor to improving maintenance of existing equipment could increase lumber output per unit log input by

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[4] Sufficient conditions for monotonicity and concavity are positive fitted cost shares and negative semidefiniteness of the bordered Hessian of second order conditions.

[5] Numbers in parentheses are the approximate standard errors calculated from the asymptotic variance formula

$$\text{Var}\ (\hat{\sigma}_{ij}) = \text{Var}\ (\hat{\gamma}_{ij})/(\bar{S}_i\ \bar{S}_j)^2,$$

where a bar above the factor share indicates the mean sample value which is treated as a constant.

TABLE 2. Parameter Estimates for the Translog Cost Function[a]

α_0	4.59* (0.09)	γ_{KL}	−0.049* (0.004)
β_T	0.005 (0.003)	γ_{KW}	−0.09 (0.007)
β_K	0.74* (0.024)	γ_{LW}	−0.09* (0.009)
β_L	0.56* (0.028)	γ_{TT}	−0.0004* (0.0001)
β_W	−0.30* (0.035)	γ_{TK}	0.004 (0.0002)
γ_{KK}	0.142* (0.005)	γ_{TL}	−0.005* (0.0003)
γ_{LL}	0.143* (0.007)	γ_{TW}	0.001 (0.0003)
γ_{WW}	0.186* (0.012)		

[a] Numbers in parentheses are the standard errors of the estimates. All coefficients are significantly different from zero at the 90% confidence level. Those indicated with an asterisk are significant at the 95% confidence level.

as much as 10%-30%, and that in many instances mill operators simply are unaware of the gains to be realized [Fahey and Starostovic].[6]

The low elasticities involving capital can be explained in part by the occurrence of biased technological change. The average annual bias, calculated by evaluating equation (11) at the mean factor share, was 1.96% for capital, 0.29% for wood, and −1.86% for labor. Factor substitution has taken place over time through investment in labor-saving capital. Indeed, had technological change not occurred, the labor share in output would have been 46.5% greater than it was in 1974. Over the twenty-five year period, total capital stock per employee more than tripled. However, the aggregate change in the capital-labor ratio actually understates the increase in real productive capital; the increase in equipment stock was almost double that of structures (478% versus 244%). This massive infusion of new investment has enabled labor productivity to increase steadily despite the release of large numbers of workers from the industry.

A recent study by the U.S. Forest Service [Wall] estimated that by the year 2000 employment in the wood products industry in western Oregon and Washington will decline by 45%, i.e., by 55,000 jobs. Substitution of capital is expected to be the principal factor, accounting for 36% of the displacement.[7] If the 1.86% annual rate of labor saving technological change estimated for the years 1950-74 continues to the end of the century, the Forest Service projection could well be an underestimate. As Stevens observed

> The prospect of a decline of this magnitude in a major industry surely deserves the attention of the public, particularly when it can be forecast some years in advance [p. 172].

In his study of Oregon's wood products industry Stevens identified two classes of workers. One group, comprising perhaps 40% of the total work force, consisted of younger, more mobile individuals who switched jobs frequently, often to non-wood products industries. In contrast, the core group was composed of older, more experienced individuals who rarely changed employers, and who were generally committed to working only within the industry.

The private and social costs of future displacement will depend upon its distribution among workers. Nationally, it is the demand for unskilled, less experienced labor which has shown the greatest decline. Between 1960 and 1970, unskilled workers as a percentage of total employes fell from 25% to 19%, whereas the percentage of craftsmen rose [Duke and Huffstutler]. The U.S. Department of Labor [1974] expects this pattern to continue. It is tempting to conclude that the peripheral labor force, which has the greatest opportunity to secure alternative employment, will bear the brunt of the displacement and, therefore, that the distributional consequences will be minimal. However, such a conclusion is unwarrantable considering the paucity of data available.

To what extent has technological innovation reduced the demand for sawlogs? The estimated bias is very small (0.29%) but positive and statistically significant. This result is inconsistent with what is known about technological innovation within the industry. For example, the development of narrower and stronger saws has reduced the amount of wood converted to sawdust and thereby increased lumber yield per unit of input [U.S. Department of Labor, 1974]. Yet, many of the innovations in the industry have occurred within the past decade and therefore might not be revealed in the data. Indeed, Williston has argued that lumber recovery per unit cubic log volume did not

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[6] These conclusions are based on unpublished data on file at the U.S. Forest Products Laboratory, Madison, Wisconsin. They were derived from sawmill efficiency studies conducted through the U.S. as part of the U.S. Forest Service financed National Sawmill Improvement Program.

[7] The remaining 9% was attributed to declining timber harvests.

improve between 1920 and 1970. It is also possible that sawlog quality has declined in ways not measured accurately by a log scale. Generally, however, the data on volume of sawlog input are crude at best and it would probably be unwise to place much emphasis on the bias estimate. For this reason it is concluded that technological progress has essentially been neutral with respect to wood input.

Inclusion of the cost function within the multivariate estimation model enables the impact of technological change on unit cost to be estimated. This impact can perhaps best be summarized by computing the rate at which average cost would have changed over time had factor prices remained constant at their initial values; that is, by evaluating the function

$$(12) \quad \frac{\partial \ell n \, AC}{\partial T} = \alpha_T + \gamma_{TT}T + \sum_i \gamma_{Ti}\ell n \, P_i$$

using 1950 prices and the estimated coefficients. The result,

$$(12') \quad \left. \frac{\partial \ell n \, AC}{\partial T} \right| \begin{matrix} P_i = P_{i,} \, 1950 \\ i = K, L, W \end{matrix}$$

$$= .00409 - .000427 \, T$$

indicates that average cost would have continued to rise slightly until about 1960, after which it would have declined slightly. This pattern is in agreement with the higher rates of labor productivity registered since 1958 [Duke and Huffstutler]. However, over the full twenty-five year period, technological change decreased unit cost by less than 1%, a rate insufficient to prevent the real price of lumber from rising.

An examination of changes in the real prices and consumption levels of lumber and two substitute wood panels (Table 3) reveals the degree to which lumber has lost its traditional markets.[8] Both panel products are less labor intensive than lumber to install which reinforced their relative price advantage. Indeed, McKillop *et al.* concluded that installation cost, as measured by the wages of carpenters, was more important than price in explaining the substitution of plywood for lumber. Particleboard is a reconstituted wood product, manufactured from low quality timber and wood residue. It holds great promise for reducing dependency upon large, high quality timber and could ultimately become the dominant wood-based panel [Buongiorno and Oliveira].

A major advantage of simultaneous estimation of the technological change parameters and the elasticities of factor substitution is that the latter can be used to derive constant-technology price elasticities of factor demand. Allen showed that these price elasticities (ε_{ij}) are given by

$$(13) \qquad \varepsilon_{ij} = S_j \, (\sigma_{ij} + \eta)$$

where η is the own price elasticity of demand for the produced good. In an early study, McKillop estimated the price elasticity of demand for lumber to be -3.2, but subsequent studies have all shown lumber demand to be price inelastic [Mills and Manthy, Adams, Berk, Buongiorno, McKillop *et al.*] with estimates between zero and -0.5 common. Equation (13) was evaluated using mean factor shares and a price elasticity of -0.6. The results appear in Table 4.

Several cross price elasticities shown in Table 4 are negative, yet all three factors are substitutes based on the elasticities of factor substitution. The negative sign arises because output is permitted to vary in response to cost changes. Thus, an increase in the price of one factor could raise costs and cause lumber demand to fall by enough to reduce the demand for all factors.

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[8] McKillop *et al.* also found substitution of steel for lumber, but complementarity between steel and plywood.

TABLE 3. Percentage Change in Prices and Consumption of Structural Wood Products, 1950-1974.

Commodity	Total Percentage Change In:[a] Relative Wholesale Price Index	Per Capita Consumption
Lumber	+33%	− 29%
Plywood	−24%	+ 251%
Particleboard[b]	−34%	+8333%

Source: Phelps

[a] Percentage change was computed in the same manner as for Table 1.

[b] Price change is measured from 1966-1974. The change in per capita consumption is measured over the entire period but represents growth from a very low base.

TABLE 4. Estimates of the Price Elasticities of Demand for Factors in the U.S. Lumber Industry[a]

	Price Elasticity of Demand for Row-Factor With Respect to Column-Price Capital	Labor	Sawlogs
Capital	−.243	−.086	−.205
	(.023)	(.018)	(.032)
Labor	−.068	−.353	−.070
	(.014)	(.025)	(.032)
Sawlogs	.071	−.040	−.377
	(.014)	(.018)	(.048)

[a] Numbers in parentheses are approximate standard errors of the estimates calculated from the following variance formulae:

$$\text{Var}\ (\hat{\varepsilon}_{ii}) = \text{Var}\ (\hat{\sigma}_{ii})/\bar{S}_i^2;\ \text{Var}\ (\hat{\varepsilon}_{ij}) = \text{Var}\ (\hat{\sigma}_{ij})/\bar{S}_i^2$$

where a bar above the factor share indicates the mean of the sample data.

Of special interest is the own price elasticity for sawlogs. Haynes linked the demand for lumber to the derived demand for stumpage by means of an elasticity of price transmission. For an assumed price elasticity of lumber −0.5, the price elasticity for west coast stumpage was estimated to be −0.32. This is slightly less than the estimate of −0.377 for sawlogs (Table 4), a result which is consistent with the theory of derived demand [Gregory].

Haynes cautioned that use of the elasticity of price transmission could lead to substantial error if structural change within the lumber industry causes the lumber/sawlog ratio to fall over time. The results of this study suggest that such change was not significant prior to 1974.

Summary and Conclusions

In this paper a cost function approach was used to estimate the production relationships in the U.S. lumber industry over the period 1950-1974. Of special interest was the extent to which the increasing scarcity of sawlogs induced substitution and technological innovation in order to reduce sawlog requirements per unit output. The results are mixed. Within a static production technology, the estimated elasticities of substitution among capital, labor and sawlogs are very small, although not so small as to imply a fixed coefficients technology. The price elasticities of derived demand were all estimated to be less than unity. The own price elasticity for sawlogs was −0.377, which is in general agreement with the results of other studies.

The substitution elasticities indicate that in the short run the sawlog/lumber ratio can be reduced by increasing labor in control and maintenance of the manufacturing process. This finding is supported by the U.S. Forest Service estimate that gains of up to 30% could be realized with equipment already in place and that failure to capture these gains is due more often to ignorance than to the high cost of labor.

Over the longer term, however, the evidence indicates that technological change has produced no significant reduction in either sawlog requirement or unit cost. In contrast, capital-using technological innovation displaced labor at the rate of 1.86% per year, a trend which is expected to continue for the remainder of the century and which could be exacerbated by declining availability of timber for harvest. An important public policy issue is whether this displacement entails significant private costs which in the interests of equity should be alleviated. Stevens has collected important baseline data on the labor force in Oregon but it is not known whether those findings can be generalized to the national industry. Additional research is also required to determine the costs of adjustment and who bears them. Since wood-based panels and lumber are frequently located in the same or nearby communities, an important consideration would be the extent to which expansion of the former might absorb workers displaced from the latter.

Finally, changes in the composition of final demand and the development of new wood products which do not require high quality sawlogs as inputs have done much to mitigate the consequences of sawlog scarcity.

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