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112

An Economic Assessment of the Lumber Manufacturing Sector in Western Washington

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Center for International Trade in Forest Products

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Center for International Trade in Forest Products
College of Forest Resources
University of Washington
Box 352100
Seattle, WA 98195-2100

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Executive Summary

Lumber manufacturing remains an economically important industry in the State of Washington. The sector has added value to Washington's timberlands and continues to generate the majority of regional timber demand. Lumber production contributes to rural economic development and employment. Lumber manufacturing has remained particularly viable in western Washington, despite macroeconomic uncertainty, regulatory constraint, and competition from foreign and other domestic producers. The last economic assessment of the western Washington lumber industry was performed in 1991 (Stevens).

This study applied classical economic techniques to provide insight into how lumber manufacturers in western Washington responded to market conditions from 1972 to 2002. Lumber manufacturing activities were investigated using a three-input Cobb-Douglas and a transcendental logarithmic (translog) cost function. Analyses were performed using a panel data set with biennial time series observations from 1972 to 2002 for sixteen western Washington counties. The measures used to assess economic performance were economies of scale, Allen and Morishima partial elasticities of substitution, own- and cross-price factor demand elasticities, and technical change. These measures were investigated at regional, biennial, and county level scales.

This study shows the western Washington lumber manufacturing sector can be modeled with nonconstant returns to scale, nonunitary elasticity of substitution, and biased technical change among the inputs capital, labor, and logs. Substantial substitution possibilities between factors of lumber production exist, and a fixed-proportion functional form like the Cobb-Douglas is inappropriate to model the lumber industry structure. The estimated translog cost function was well-behaved and an appropriate choice of functional form for the western Washington lumber industry.

Lumber production costs are most sensitive to the price of logs, followed by the price of labor and least impacted by the price of capital. Mean cost share values for logs, labor and capital are 58, 24 and 18 percent, respectively. At the regional level, sawmills have captured economies of scale in the production of lumber. A 10 percent increase in output resulted in a 0.418 percent reduction in costs. Economies of scale values jumped during the 1980s recession as firms produced radically less output and faced higher input costs; values subsequently declined as firms exhausted scale economies during times of harvest level reductions in the 1990s.

At the regional level, Allen and Morishima partial elasticities of substitution agreed that all inputs were inelastic substitutes with the greatest substitutability between capital and labor and least substitutability between logs and labor. Capital demand was the most own-price responsive and log demand the least. Cross-price demand elasticity was greatest between capital and labor; cross-price elasticities for all input combinations including logs were near zero. Demand for logs was highly inelastic with respect to own-price and the price of other inputs. This pattern was relatively consistent across time and across counties, although at finer scales greater evidence of complementary between inputs was noted.

Expansion of lumber production and capacity over time primarily occurred in Lewis, Pierce, Clallam, and Cowlitz Counties owing to new sawmill infrastructure. Gains in Cowlitz County were primarily made from investments in existing mills. Lewis gained one large mill in 1998, increasing the total number of large mills to seven, but additions in existing sawmills contributed to increase capacity. The number of large mills in Pierce County remained constant from 1996 to 2002; capacity investments in existing mills led to increased lumber output. Although capacity in Snohomish County sawmills rose, the loss of three large mills between 1998 and 2002 caused an overall decline in lumber production. Results point to processing capacity centers developing in two areas, Clallam County on the Olympic Peninsula and counties along the I-5 corridor south of King County. Restructuring of log export markets, proximity to Interstate-5, and port access seem to be factors in industrial expansion, but the magnitude is unknown.

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1. Introduction

In 2002, 17.3 million acres representing 41 percent of the state of Washington were classified as timberland, defined as forestland capable of being managed for timber production. These lands contained 327 billion board feet of timber growing stock, producing 4.6 billion board feet of lumber and sustaining 8.8 thousand sawmill manufacturing jobs statewide (Smith et al., 2004, U.S. Census Bureau, 2002b). However, these figures do not fully reflect the importance of the forest industry from a public policy perspective.

First, there is particular interest in maintaining forest sector employment, which has traditionally been concentrated in rural areas with few other employment opportunities (Forest Ecosystem Management Assessment Team, 1993). Between 1972 and 2002, the number of sawmills in western Washington fell from 122 to 57 mills, a 46 percent decline. Despite this drop in mills, maximum eight-hour shift capacity increased from 8.2 to 10 million board feet over the same period. After 1998, capacity expansion differed from previous patterns of locating sawmills in rural areas near major timber supply centers. Data suggest that sawmill owners are forgoing construction of new mills in rural locations in favor of areas with well developed manufacturing sectors and transportation infrastructure. In addition, capacity has concentrated into fewer large mills producing commodity lumber from an increasingly homogeneous log supply. Capacity expansion patterns raise concerns for rural employment and community stability as well as forest management.

Second, pressures from urban development and land use conversion have made maintaining the remaining forest base a priority. Nationally, the USDA Forest Service has identified land use conversion and loss of open space as one of four threats to management of national forests and grasslands in the United States. The State of Washington also recognized the value of maintaining forestland when it passed the Forest Tax Law of 1971. Property taxes assessments for qualifying forest and open space landowners are based on current land use, rather than highest and best use, which can encourage conversion (Washington State Department of Revenue, 2007). Lumber manufacturing provides a market where landowners that choose to manage these forests can sell timber at harvest time. Thus, a viable lumber industry is crucial for maintaining the working forests that discourage land use conversion.

These two policy concerns may be analyzed using classical economic techniques involving production theory. Producing lumber requires inputs of labor, capital and timber. Couching the mix of inputs into a production framework and analyzing this framework is the aim of this study.

This study focuses on the western Washington lumber industry, which has faced a multitude of challenges over the last 30 years driven by sector-specific economic and policy shocks. Lumber producers experienced a period of sustained growth brought about by rising lumber price as the nation recovered from a recessionary period in 1975. Beginning in 1980, a severe nationwide recession depressed new housing construction; the subsequent collapse of lumber demand and prices ultimately led to widespread mill closures. Surviving mills retooled and made investments in labor-saving processing technology to increase productivity and efficiency. Reduced timber markets and low prices in Washington culminated with the U.S. government buying back high priced federal stumpage sales rather than forcing timber sale contract holders to default on those contracts. The economy recovered by the late 1980s and record levels of housing starts resulted in record high lumber prices in 1993 (Sohngen and Haynes, 1994). This boom period for the lumber industry was halted by market chaos as regulatory constraints led to the withdrawal of federal timber to preserve old-growth habitat. Supply shocks and high log prices led to mill closures as resource availability became a major concern. The late 1990s were marked by a striking decline in log exports to the Pacific Rim following the Asian financial crisis in 1997, loss of premiums for high-quality logs, further globalization of wood supply sources, and increased manufacturing of engineered wood products (Lippke, Braden, and Marshall, 2000; Daniels, 2005).

The objective of this study is to apply economic techniques to provide insight into how lumber manufacturers have responded to market trends from 1972 to 2002. Previous studies of lumber production in Washington have examined log to lumber recovery and overrun factors (Cardellichio 1986), disproportionate job impacts between skilled and unskilled sawmill workers (Stevens 1991), and the nature of technological change (Weiner 1996). This study contributes to Washington lumber production literature in several ways. The lumber industry is examined over a longer time period than the previous studies. The data set contains biennial observations from 1972 to 2002, spanning three decades with known market perturbations. This expands the data set used by Weiner, which ended with 1990, making this the only known study of western Washington lumber manufacturing containing any information from the 1990s. In addition, previous studies differed by both geographic and temporal scales of analysis. Here, western Washington is analyzed as a region, by county, and by each biennial data period. Regional analysis provides results that can be compared to other studies while county and biennial results provide insight into the localized impacts and timing of firm response to changing market conditions.

Trends in lumber manufacturing are primarily examined through scale economies, substitution and price elasticities, and technical change estimation at three different scales. Nine hypotheses will be examined. These hypotheses were derived from various issues raised in past studies and economic theory, such as functional form and the nature of production coefficients. In addition, the expansion of lumber production capacity in the last decade raises questions about the differential impacts on labor, capital, and stumpage. These hypotheses are:

- Results were robust to the choice of production models,
- The lumber production function met required curvature assumptions,
- The proportion of capital, labor, and log production inputs remained fixed,
- Lumber producers enjoyed increasing returns to scale,
- Inputs were substitutes in the lumber production process,
- Demand for inputs was responsive to relative changes in input prices, and
- Firm behavior differed by location and over time.

This study begins with a summary of background information about the lumber manufacturing sector in western Washington. Next is the review of relevant literature followed by a section summarizing production theory. The next section contains the econometric models and is followed by a data section. Results are then displayed, along with comparisons of findings from previous studies. Discussion, conclusions, policy implications, and recommendations for further study bring the analysis to a close.

2. Background

This section is intended to provide background information about the lumber manufacturing sector in western Washington. Western Washington, or the westside, lies west of the Cascade Mountain crest and encompasses 19 counties (Figure 1). All 19 counties contained active sawmills during some part of the study period.

Figure 1. Counties of western Washington

The interaction of markets for stumpage, logs, labor, and capital, along with trends in the United States economy, influence the supply and demand for lumber. Lumber production begins in the forest where trees are harvested and logs are sold. Once the logs reach the mill, additional labor and machines process the logs into lumber. Lumber is then distributed to final consumers for a variety of purposes, primarily housing construction, repair, and remodeling.

Because demand for wood products is driven primarily by demand for residential and non-residential construction, business cycles, construction activity, and interest rates over the study period are discussed first. Then, the lumber industry in western Washington is highlighted, including trends experienced in output and factor inputs markets. Trends in timber supply and log, labor, and capital markets are presented last. A description of data sources used for this section is provided in Appendix A.

2.1 United States Economy

Sawmill production levels are influenced by a variety of macroeconomic variables, both domestically and internationally. In the U.S., lumber is primarily consumed by the construction sector; economic trends that directly or indirectly impact commercial and residential construction impact the lumber industry. The next section discusses the business cycles, construction activity, and interest rates that have impacted western Washington sawmills over the study period.
Business cycles—Periods between economic recessions and expansions are business cycles. Table 1 shows the five recessions in the U.S. economy between 1970 and 2002 reported by the National Bureau

of Economic Research (National Bureau of Economic Research, 2006). In general, during recessionary periods, demand for construction materials declines because housing demand declines. Domestic log markets are depressed from reduced demand for lumber and other wood products, resulting in low timber and commodity lumber prices, mill shutdowns, and unemployment. In contrast, during periods of high economic activity (an expansion), construction demand increases. The cycle that began in November 2001 was an exception to this trend; although economic activity declined for several periods, the housing market remained strong. Nonetheless, increased demand for wood construction materials usually heralds an increase in stumpage, log, and lumber prices and forest sector employment as mills compete for resources, all else constant (Wiseman and Sedjo 1985).

Table 1. U.S. business cycles, 1970 – 2002

Study period business cycles		(in Months)	
Trough	**Peak**	**Trough from previous trough**	**Peak from previous peak**
November 1970	November 1973	117	47
March 1975	January 1980	52	74
July 1980	July 1981	64	18
November 1982	July 1990	28	108
March 1991	March 2001	100	128
November 2001		128	

Interest rates—Interest rates indirectly impact the lumber industry because they are a key determinant of investment in residential and non-residential construction by firms and consumers. Low interest rates encourage borrowing. Purchases of homes increase because favorable lending rates make mortgage payments more affordable. High interest rates have the opposite effect; terms of lending make investment less affordable and raise monthly mortgage payments. Consumers may postpone decisions to purchase a new home until rates are more favorable. Firms faced with high interest rates may postpone building new factories because the cost of borrowing is too high. Figure 2 illustrates the inverse relationship between interest rates (measured by the U.S. Bank Prime Loan Rate, adjusted for inflation) and lumber production from the Washington Department of Natural Resources (WADNR, 1972-2002a).

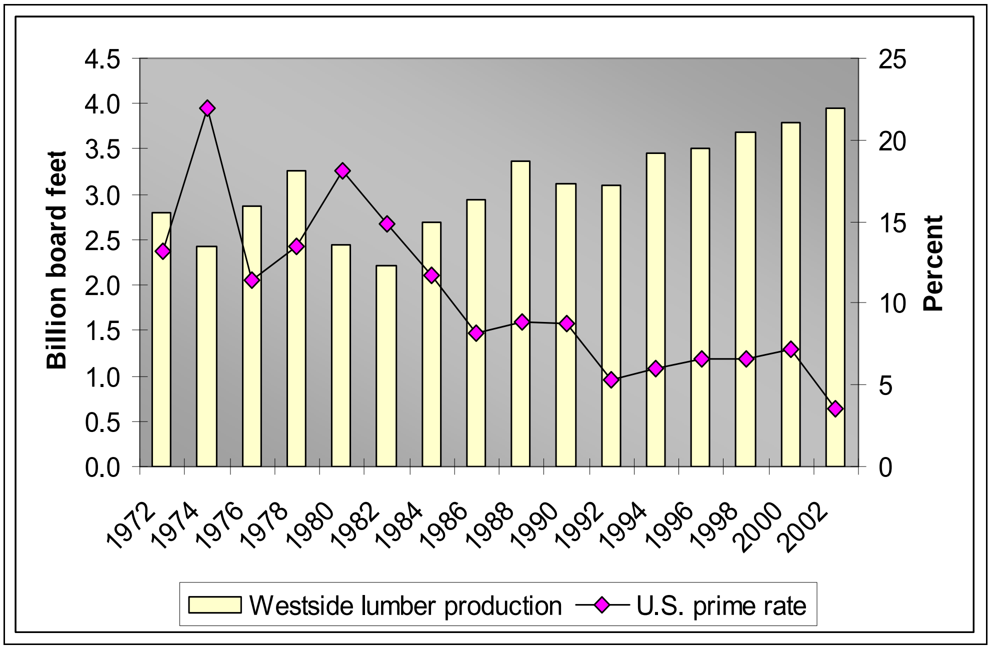

Figure 2. Real interest rate and western Washington lumber production

Construction-- Cycles in construction activity, driven by business cycles and interest rates, lead to volatility in the lumber industry. Figure 3 illustrates the cyclic nature of construction activity and the relationship between construction and lumber production. The left axis shows volume of Washington westside lumber production (WADNR, 1972-2002a). The right axis represents the annual value of U.S. residential and non-residential construction put in place, in billion 1982 dollars (U.S. Department of Commerce, Bureau of the Census, 1972-2002a). The graph shows that declining construction in response to recessionary pressures in the 1970s, 1980s, and 1990s was consistently accompanied by falling lumber production. Similarly, periods of increased construction demand led to growth in lumber production. Construction expansion in the 1990s was especially strong and heralded a period of unprecedented lumber production levels in western Washington.

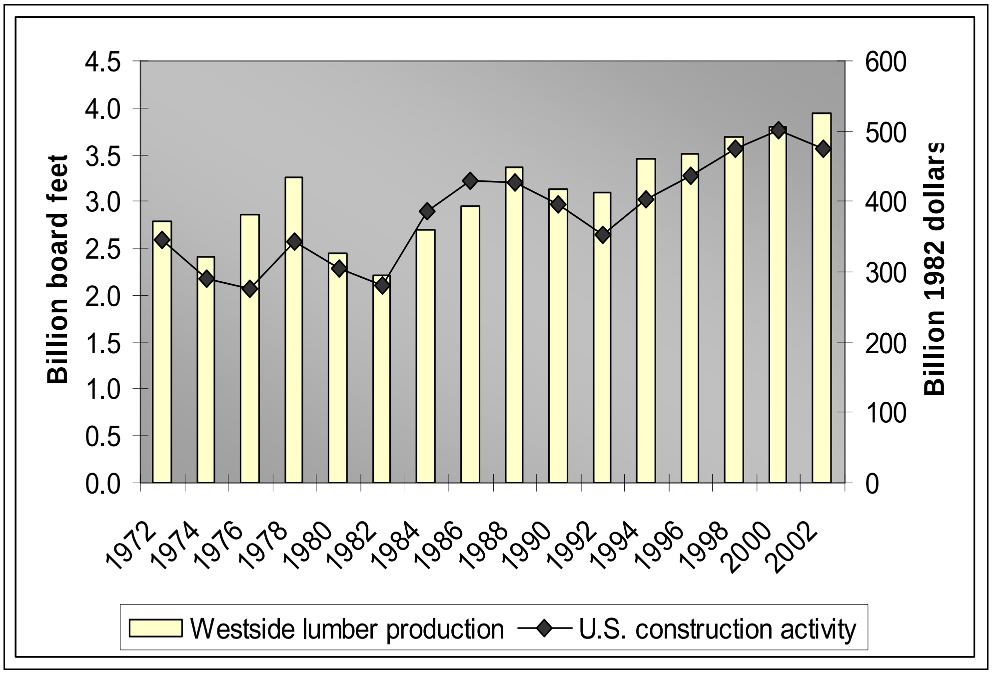

Figure 3. U.S. construction and western Washington lumber production

2.2 Lumber Production

The Washington Department of Natural Resources gathers mill-level lumber production, eight-hour maximum milling capacity, and log consumption information for the biennial Washington Mill Survey (WADNR, 1972-2002a). These mill-level values have been aggregated to the regional and county level for this analysis. Figure 4 shows western Washington lumber production and prices over the study period. Lumber prices are reported for the Pacific Northwest region in Warren (1972-2002) and deflated to constant 1982 U.S. dollars using the all-commodity Producer Price Index. Lumber production and prices generally trend together until prices peaked at $427 per thousand board feet in 1994. After that year, prices dropped dramatically to reach an all-period low of $240 per thousand board feet in 2002. At the same time prices were falling, lumber production increased to a peak high of 3.9 billion board feet in 2002. This trend implies that sawmills increased production to maintain revenue levels when faced with falling output prices. Another explanation is that investment in technology improved efficiency in western Washington sawmills, allowing production to expand despite declining prices.

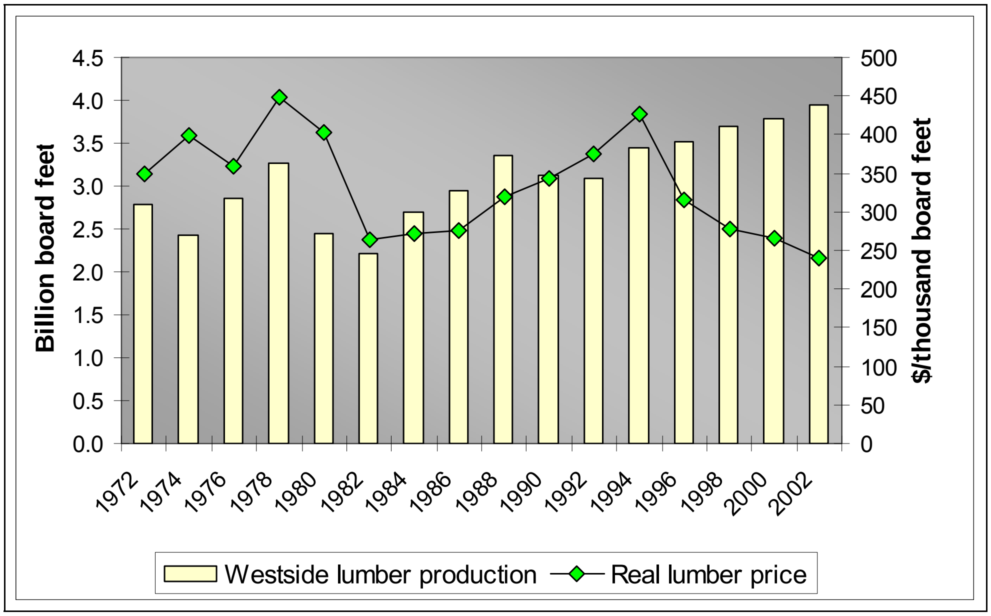

Figure 4. Western Washington lumber production and real lumber prices

Using the WADNR mill survey data, lumber manufacturing in western Washington can be examined at a finer geographic scale to highlight regional trends in production. County-level lumber manufacturing volumes are shown in Figure 5. The bars represent each county's proportion of total lumber volume produced over the study period. The majority of lumber production occurred in Cowlitz, Grays Harbor, Lewis, Mason, Pierce, and Snohomish Counties. Mill closures effectively ended the lumber manufacturing industry in Kitsap and King Counties in 1995 and 2001, respectively. The opening of two large mills in 1994 led to notable increases in lumber production in Clallam County. Overall growth in lumber production is related to capacity expansion and product recovery, which are discussed next.

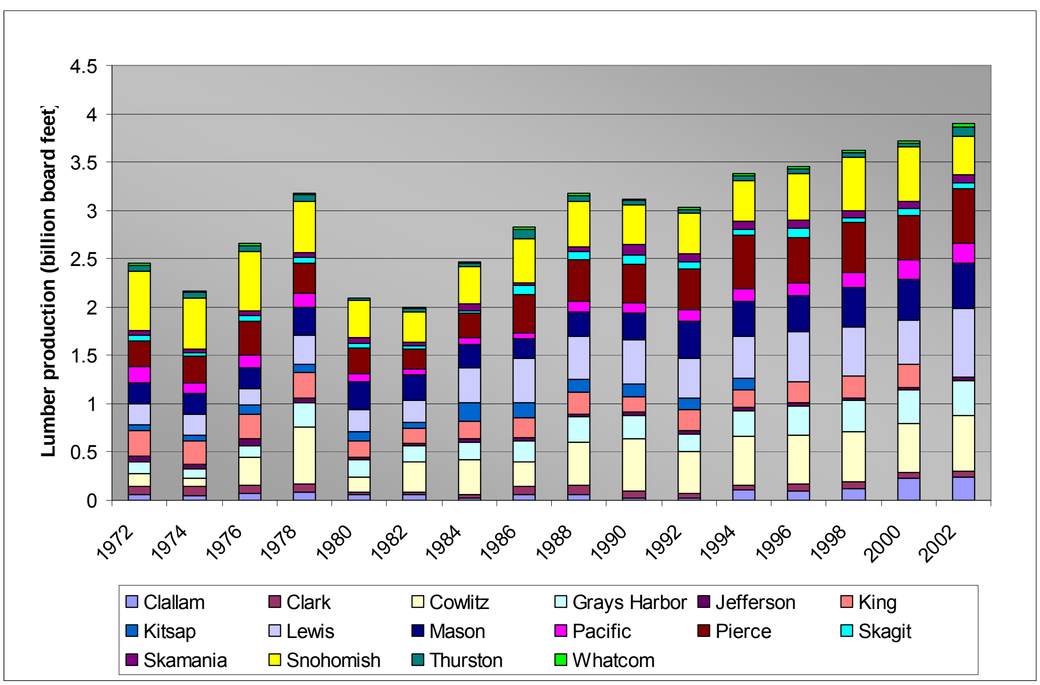

Figure 5. Western Washington lumber production by county

Capacity expansion--Figure 6 shows western Washington eight-hour maximum lumber manufacturing capacity from 1972 to 2002. Strong lumber markets heralded an increase in capacity increase during the later half of the 1970s. The recession of the 1980s caused significant disruption in construction activity, which is reflected in the loss of sawmill capacity in 1980 and 1982. After another dip in 1986, lumber manufacturing capacity displayed an increasing trend with peaks in 1994 and 2000.

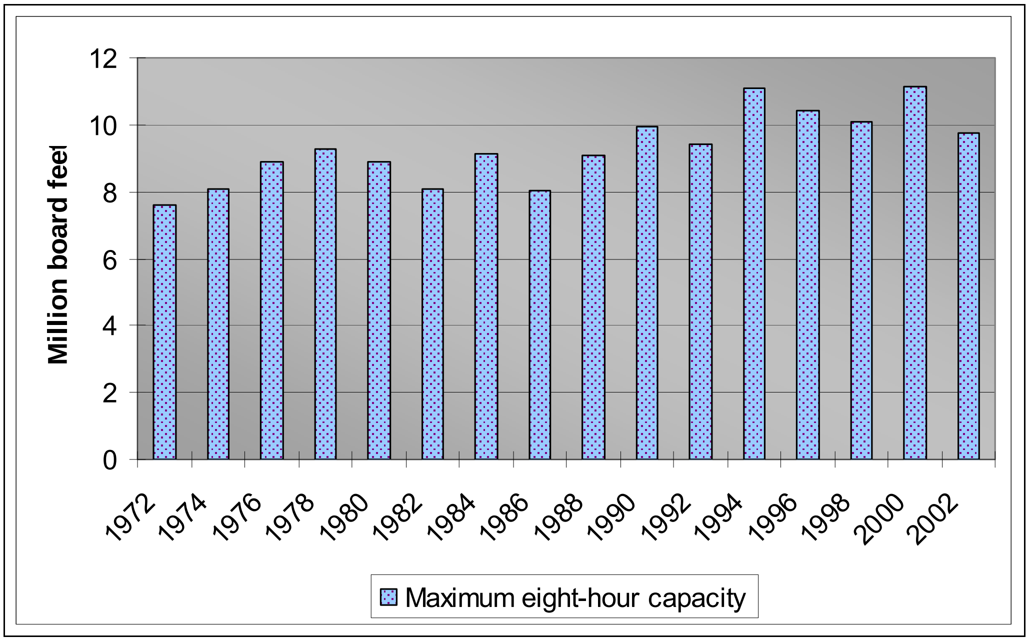

Figure 6. Western Washington sawmill capacity

Figure 7 shows sawmill capacity at the county level. Recall that in Figure 5, sawmills in Cowlitz, Grays Harbor, Lewis, Mason, Pierce and Snohomish Counties consistently produced the most lumber. Figure 7 shows that these counties contained the greatest concentration of manufacturing capacity as well, highlighting the relationship between lumber production and sawmill capacity.

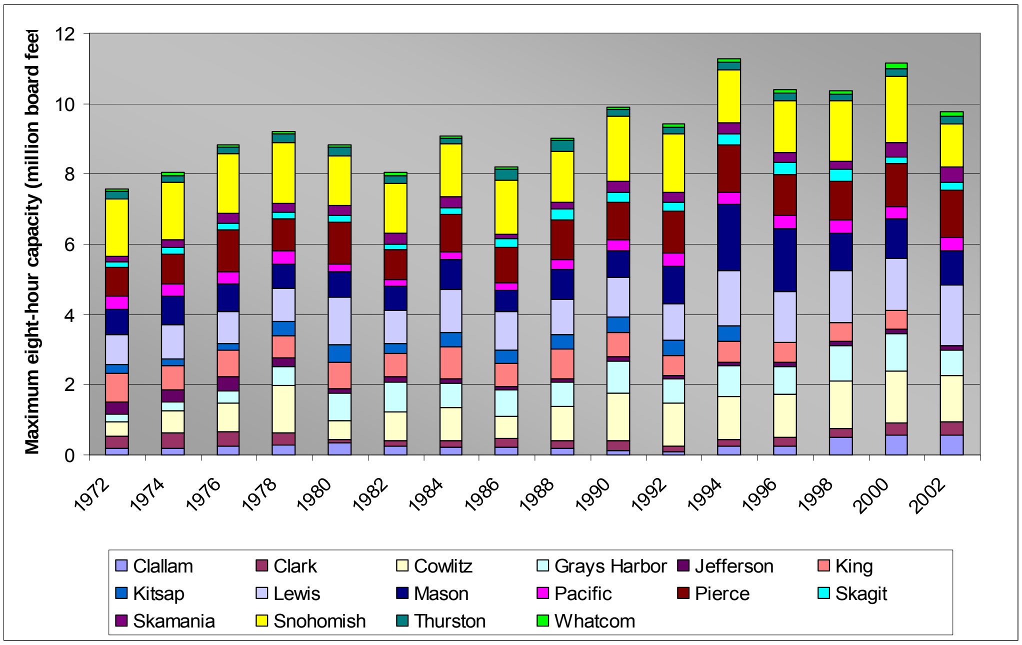

Figure 7. Western Washington sawmill capacity by county

The size of mills also changed from 1972 and 2002. To illustrate, Figure 8 displays the number of western Washington sawmills by mill size from WADNR survey data. Mill size is classified according to capacity (thousand board feet, lumber tally) per eight-hour shift; class A mills have the largest and class D mills the smallest capacity. As evident in Figure 8, the number of B, C, and D size classes have declined since the 1970s. The decline in the number of class D mills from 67 in 1972 to 11 in 2002 is especially dramatic. On the other hand, class A mills increased in number from 26 to 32; by 2002, over 85 percent of production capacity in western Washington was concentrated in large capacity mills. Thus, between 1972 and 2002, the lumber industry in western Washington experienced both a drastic decline in the number of mills and a drastic increase in concentration of manufacturing capacity into large scale mills.

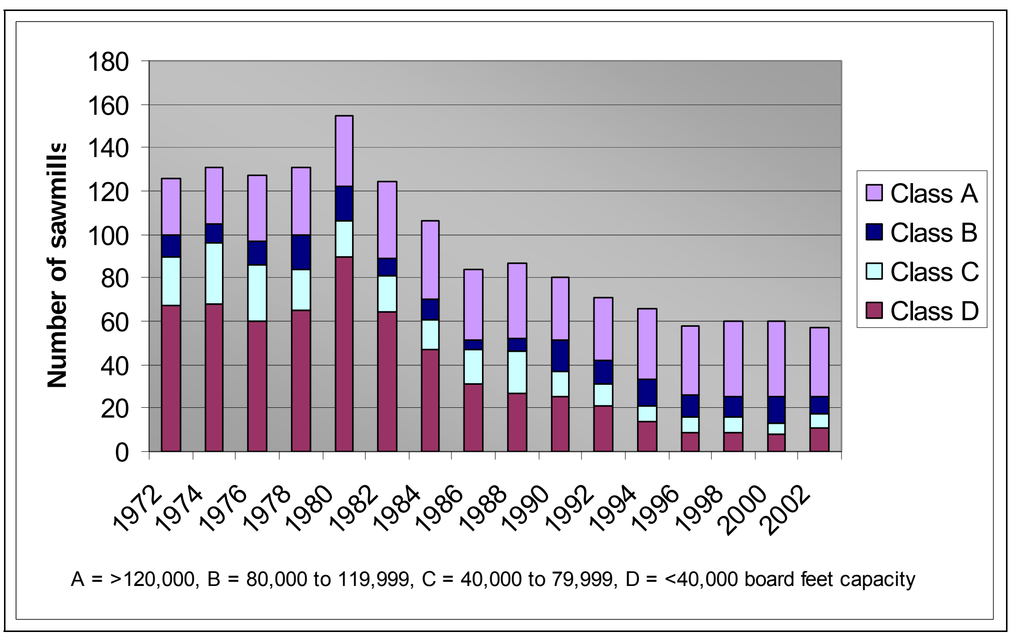

Figure 8. Number of western Washington sawmills by mill size

Lumber recovery—A lumber recovery factor (LRF), or overrun, is the ratio of lumber output per unit of log input. For example, in 2002, western Washington sawmills used approximately 1.9 billion board feet (Scribner) of logs to produce 3.9 billion board feet of lumber (lumber tally), an LRF of 2.0. Lumber recovery rates in Figure 9 exhibit a rising trend, nearly doubling between 1972 and 2002. The greatest gains occurred between 1988 and 2002 when overrun increased by 44 percent.

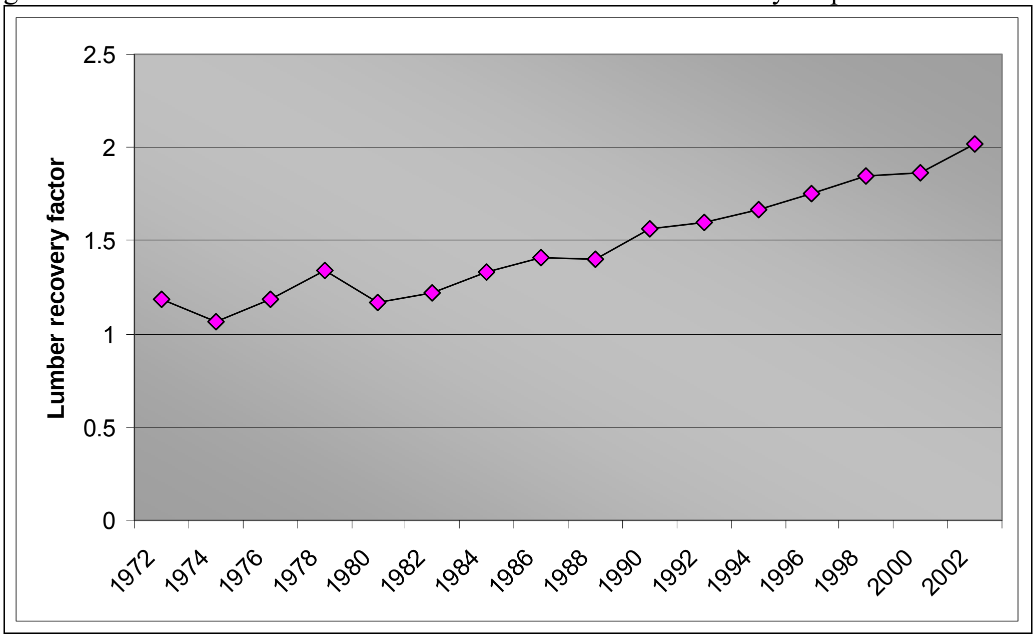

Figure 9. Lumber recovery improvements in western Washington sawmills

Rising lumber recovery rates are attributed to improvements in technology and smaller log sizes. Technological improvements have increased manufacturing efficiency in several ways. Computerized log size (diameter and length) sensing capabilities determine the optimal sawing pattern to maximize the volume or value recovered from each log. Improved sawing accuracy reduced the amount of size variation in sawn lumber, increasing solid wood recovery. Thinner kerf saws reduced the proportion of the log ending up as sawdust.

In addition, overrun values have been influenced by the changing timber resource in western Washington. As harvesting has shifted toward second growth forests, the average log size available to lumber processors has decreased. Only about 15 percent of timber processed in western Washington in 1972 came from trees less than 10 inches in diameter (breast height). By 2002, that value had risen to 76 percent (Keegan et al. 2006). As log diameters decrease, the Scribner log rule (used throughout the Pacific Northwest) underestimates the volume of lumber that can be recovered from each log, creating artificial gains in overrun. Efficiency likely has improved in western Washington sawmills, but the magnitude of improvement is obscured by overrun calculation error inherent in the Scribner log rule.

2.3 Timber Harvest

Figure 10 displays the all-species timber harvest on public and private forest land in western Washington from 1972 to 2002. Harvest data come from the Washington Harvest Report published annually by the Washington Department of Natural Resources (WADNR, 1972-2002b). Harvests in western Washington declined from 5.8 to 2.7 billion board feet over the study period, a 46 percent drop. The majority of harvesting occurred on private lands; although private harvests have fallen, they remained relatively stable over the study period. Timber harvesting on public lands curtailed sharply in the 1990s in response to cut backs in federal timber sale volume owing to the listing of the northern spotted owl (*Strix* *occidentalis* Caurina) as threatened throughout its range. Subsequent listing of the marbled murrelet (*Brachyramphus marmoratus*) and requirements to protect salmon in riparian areas on both public and private lands reduced allowable harvest levels further. Between 1990 and 2002, regulatory constraints alone reduced harvest volumes in western Washington by 40 percent (Daniels, 2005). This is surprising given that lumber production increased by almost 8 million board feet over the same period.

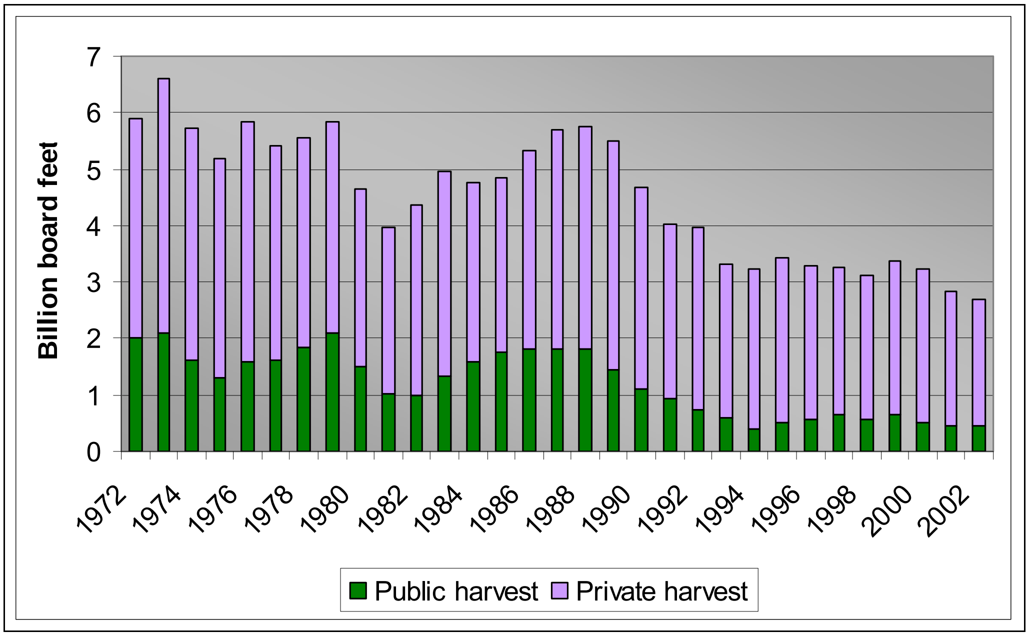

Figure 10. Public and private western Washington timber harvest

Figure 11 shows western Washington timber harvest by county. The majority of timber harvesting between 1972 and 2002 occurred in Cowlitz, Grays Harbor, and Lewis Counties. Clallam, Jefferson, Pacific, King, and Skamania Counties began with moderate harvest levels that curtailed around 1990, partly reflecting the proportion of public forests in those counties. Clark, Kitsap, Pierce, Thurston, and Whatcom Counties experienced relatively low levels of timber harvesting throughout the data period.

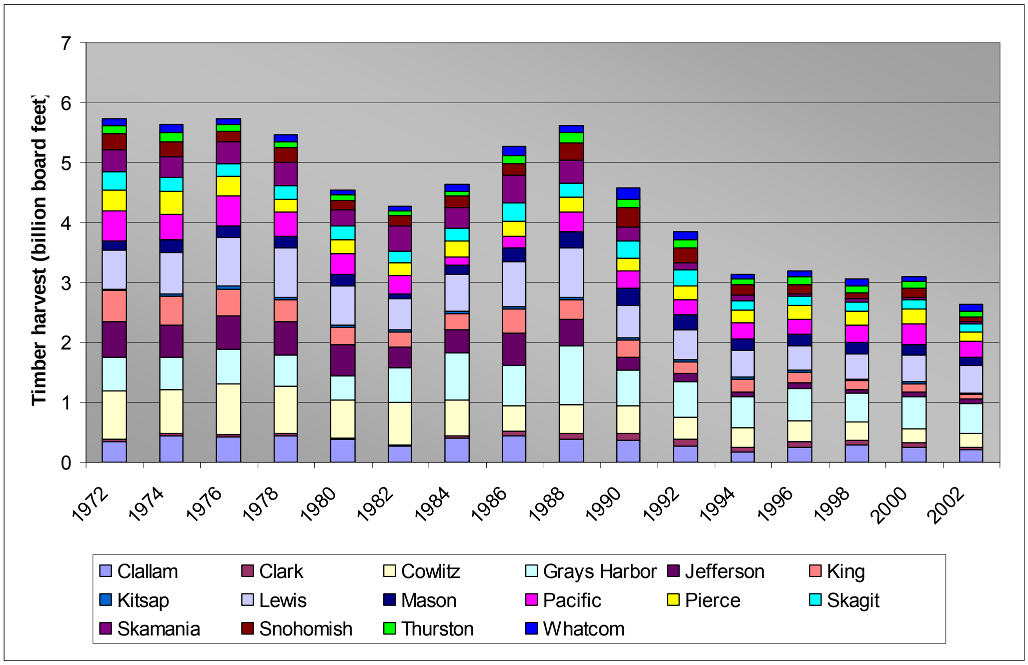

Figure 11. Western Washington timber harvest by county

2.4 Logs

Logs are the primary raw material for lumber and other wood products. Feedback from demand in lumber markets directly influences log prices and consumption (Haynes, 1977). Figure 12 shows log consumption in western Washington sawmills and real (1982) log prices over the study period. Log consumption data are available in the WADNR Mill Surveys; log prices are constructed from three sources described later in the data section. Prices generally followed trends in log consumption until the spike in 1994. After peaking near $450 per thousand board feet in 1994, log prices dropped to $290 per thousand by 2002. Declining log prices are generally attributed to the loss of log export price premiums following the Asian financial crisis of 1997. Log consumption remained around 2 billion board feet over the same period, suggesting that mills were able to achieve some cost savings as logs formerly sent to the Pacific Rim were channeled back into domestic markets.

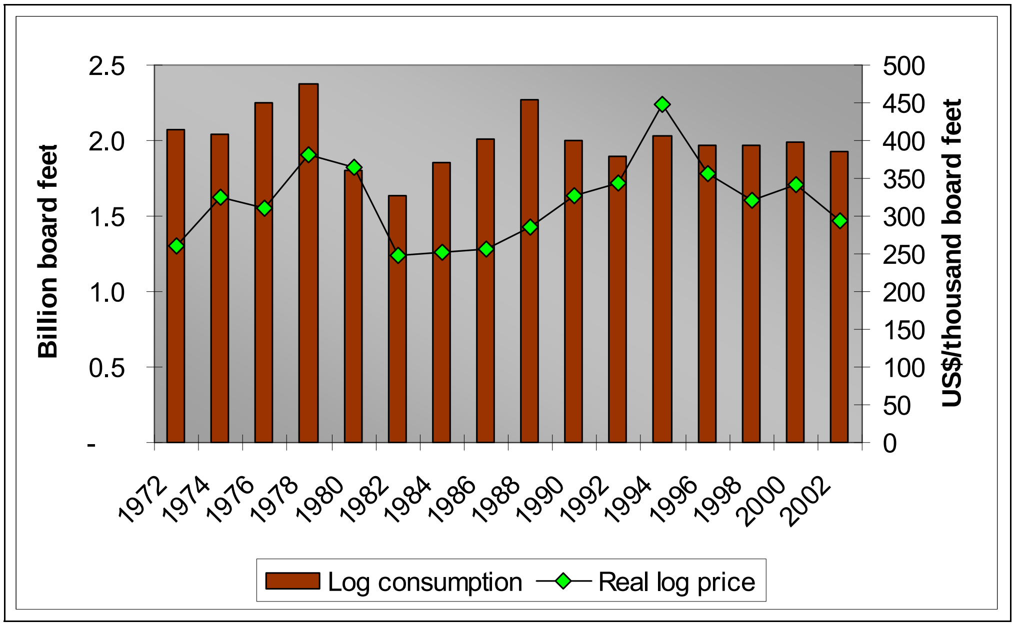

Figure 12. Western Washington log consumption and log prices

Log exports--The decline of log exports and increased supply of logs for domestic processing is illustrated in Figure 13. The bars indicate the volume of logs exported from the Seattle and Columbia-Snake Customs Districts to all destinations from 1972 to 2002 (Warren, 1972-2002). The line shows the difference between the volume of westside Washington timber harvest (all owners, all species) and log exports (WADNR, 1972-2002b). Log exports peaked in 1988 and then dropped sharply until leveling off in 1994. This decline is generally attributed to harvest reductions on public forestland, as discussed above. However, the second drop in log exports after 1996 resulted from collapsed demand for logs in Pacific Rim markets following the Asian financial crisis (Daniels, 2005). This channeled about one billion additional board feet of log volume into domestic markets. The “new” source of raw material may help explain the sawmill capacity and lumber production expansion observed in western Washington over the same period.

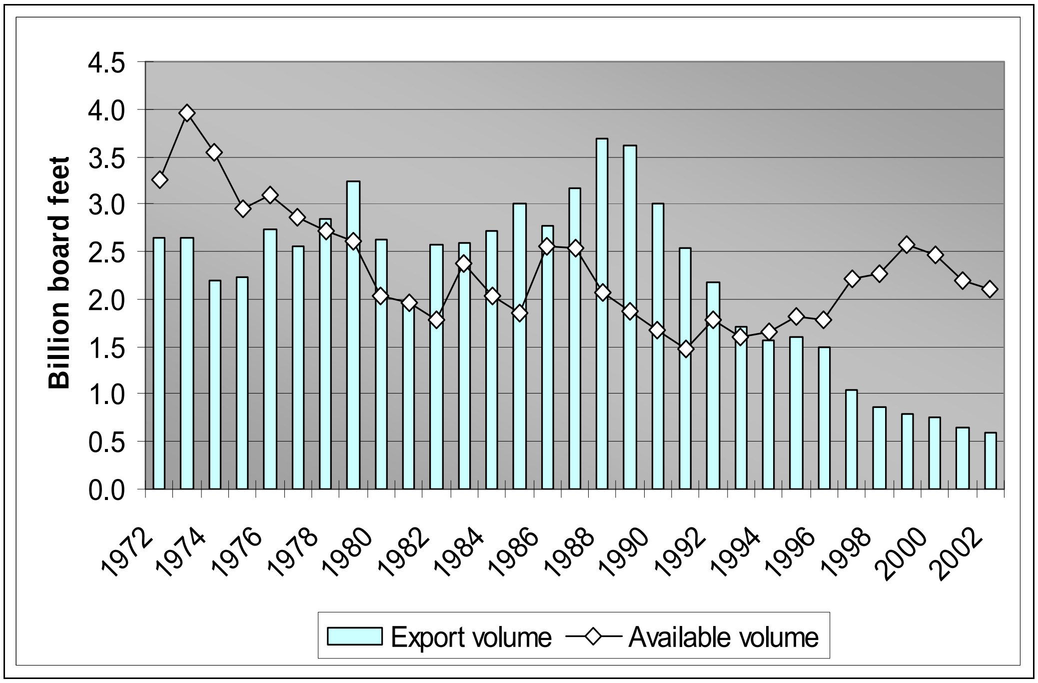

Figure 13. Log exports and log volume available to domestic processors

2.5 Employment

Demand for lumber impacts lumber manufacturing jobs in sawmills. Figure 14 displays the number of persons employed in western Washington lumber manufacturing at the 242 SIC level and the 3211 NAICS level from 1972 to 2002 (U.S. Census Bureau, 1972-2002). The method for reconciliation between SIC and NAICS codes is discussed later in the data section. Sawmill employment peaked just shy of 16 thousand workers in 1978 and fell to about 9 thousand workers by 1982; mill closures caused almost half of the workforce to lose their jobs. Subsequent employment losses throughout the 1990s were driven by investments in automation and labor saving technology to cut labor costs and capture scale economies by expanding production of commodity grades. This shift to capital-intensive large output mills occurred industry-wide, ensuring that sawmill employment never returned to pre-1982 levels. By 2002, employment in the western Washington lumber industry reached an all-period low of 7 thousand jobs. Total sawmill payroll generally followed employment trends.

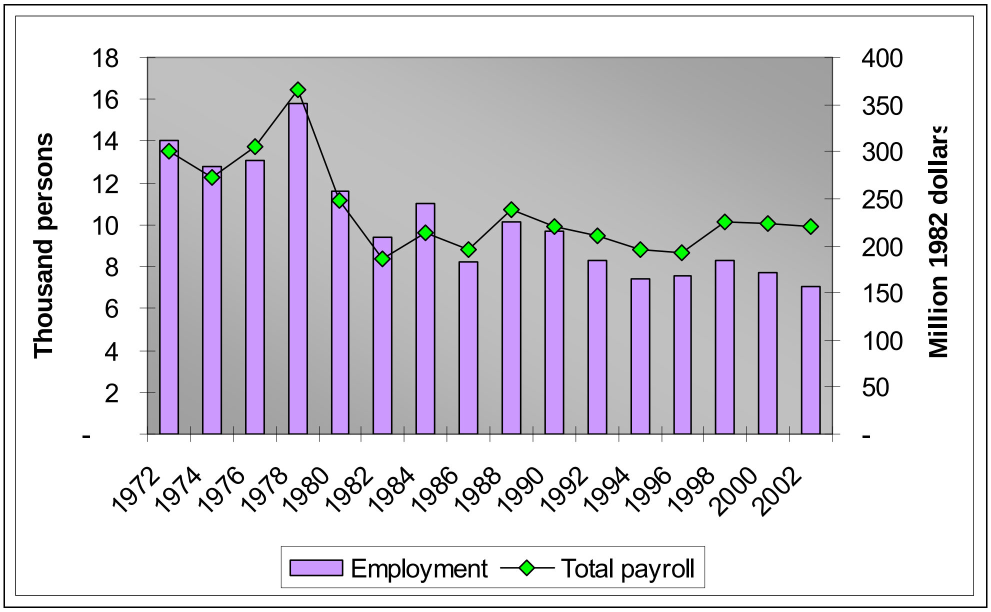

Figure 14. Western Washington sawmill employment and total payroll

Sawmill employment by county shows where employment reductions had the greatest local impact. Interestingly, the greatest losses of employment occurred in counties with the most industrial capacity and the greatest lumber production. Figure 15 shows that Cowlitz, Grays Harbor, and Snohomish County mills experienced the greatest loss of employment between 1972 to 2002. Employment in other traditionally strong players like Lewis and Mason Counties stayed fairly consistent, while Pierce County showed an increase. Overall, when comparing the 1972 bar with the 2002 bar, sawmill employment losses in Cowlitz, Grays Harbor, and Snohomish Counties are the most pronounced. Yet, these counties were able to gain market share of lumber production over time, indicating that something was changing in western Washington sawmills.

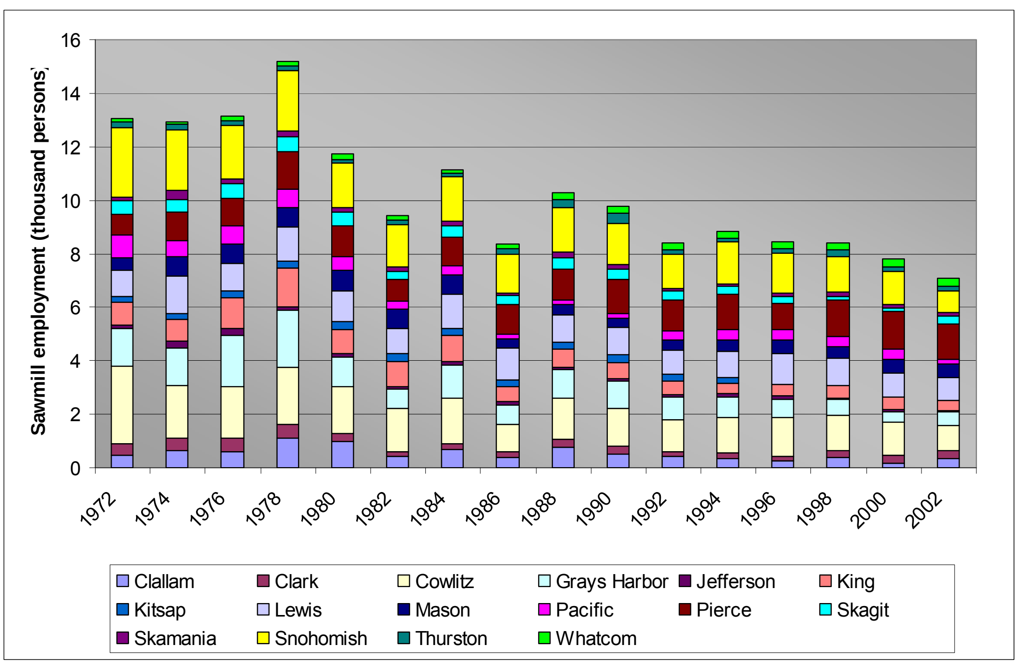

Figure 15. Western Washington sawmill employment by county

The manufacturing sector is often a source of high wage jobs for skilled workers, making it a key component of the regional economic base. Figure 16 compares employment in the sawmill sector with all other western Washington manufacturing employment. The lumber employment share of all manufacturing jobs reached a peak of 7 percent in 1972. By 2002, lumber manufacturing accounted for 3 percent of all westside manufacturing jobs. The graph implies that lumber producing facilities have made a minor contribution to the western Washington economy. This may be misleading because lumber manufacturing employment has traditionally been located in rural areas where few high wage jobs are available to skilled workers. The impact of sawmills is in location of jobs, not number of jobs.

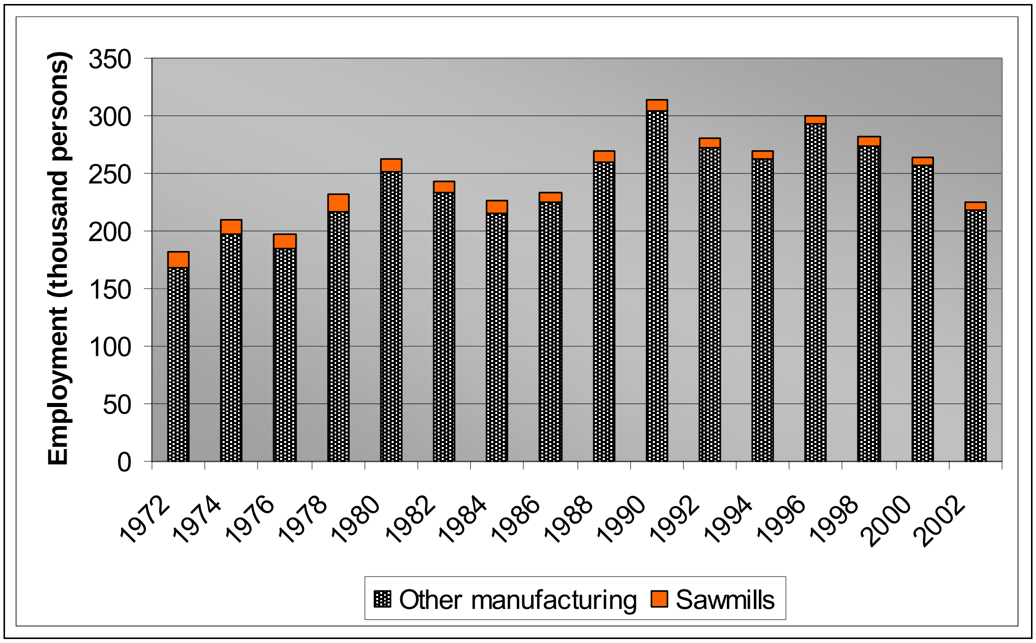

Figure 16. Manufacturing and sawmill employment

2.6 Capital

The lumber industry made capital investments to improve operating efficiency in sawmills. Physical capital and financial capital are needed as firms expand or innovate. Physical capital includes sawmill infrastructure of land, buildings, machinery, and equipment. Sawmills compete for access to financial capital, such as loans from banks, with other businesses. In boom times, firms requiring financing to expand may find limited access to investment funds.

Figure 17 shows the assessed real building value (1982 dollars) of sawmills responding to the WADNR Mill Survey and real interest rates over the study period. Assessed sawmill values are a proxy for capital investment; real interest rates provide a measure of the cost of borrowing. Assessed real property values were obtained from visiting each of the 19 westside County Assessor offices. Investment and interest rates were inversely related until 1980 when recession brought declining lumber demand that reduced sawmill investments despite low interest rates. After the recession, an economic recovery combined with no appreciable rise in the cost of borrowing helped to stimulate investments in sawmills. Although interest rates fell in 1992, sawmill assessed values remained flat as the supply shock in public timber raised fears about log availability. By 1996, investment rebounded, led by low interest rates and high housing demand.

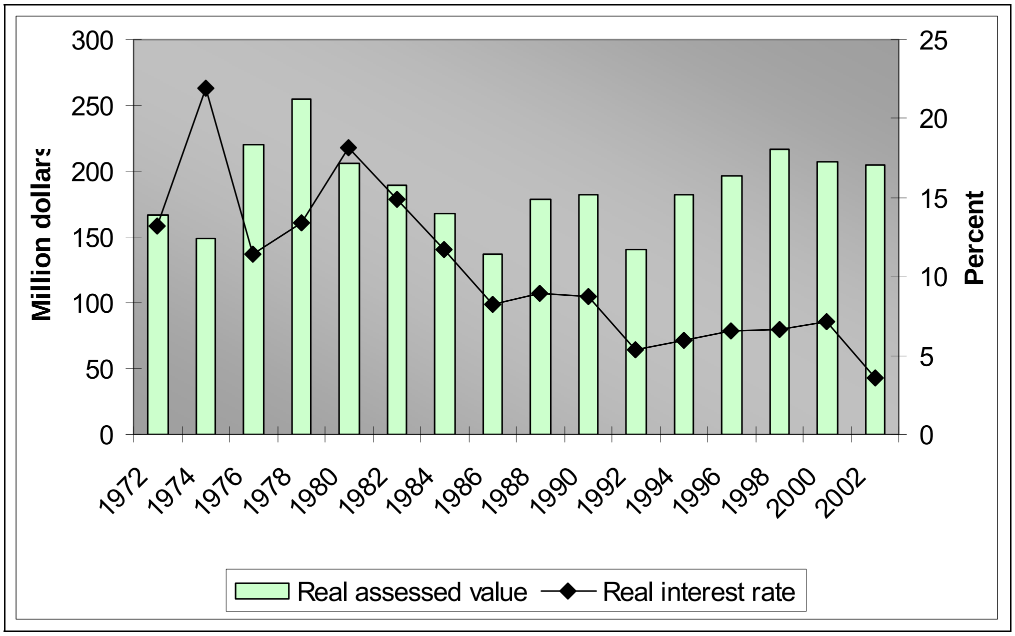

Figure 17. Assessed value of western Washington sawmills

Additional trends in capital investment can be observed by examining the assessment values for sawmills in each county. Figure 18 shows that the majority of real property investment in lumber manufacturing early in the study period occurred in Cowlitz and Grays Harbor Counties. The leap in Grays Harbor investment between 1976 and 1984 resulted from new mill construction. The 1990s saw capital investment rise in Clallam, Lewis and Pierce County sawmills, reflecting new capacity and production expansion in those counties.

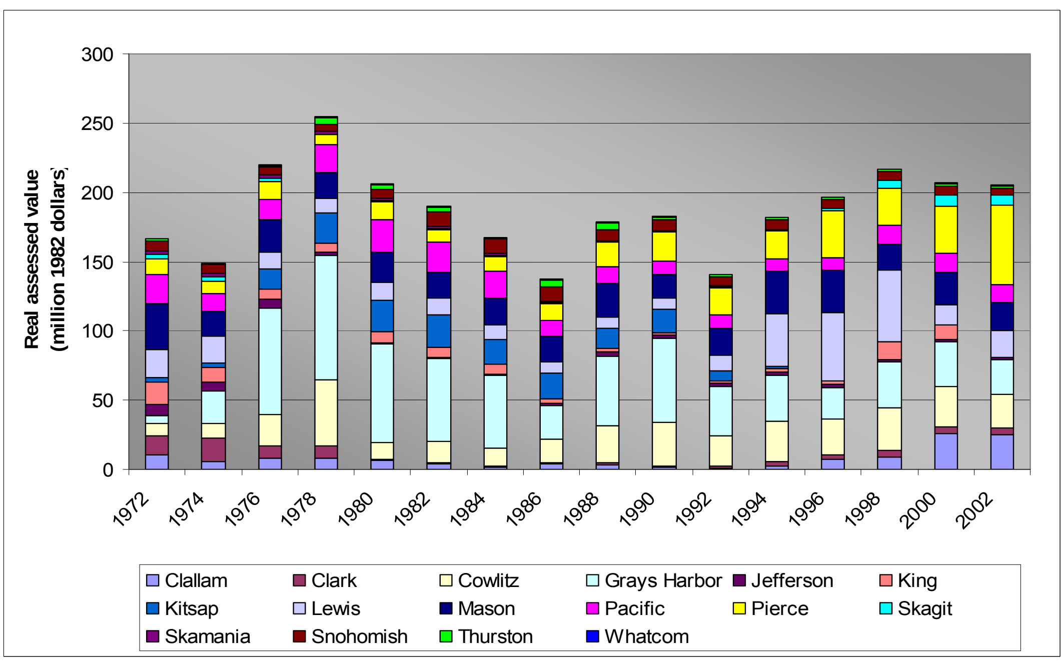

Figure 18. Assessed value of sawmills by county

This background section has highlighted trends in western Washington lumber production resulting from interactions between the macroeconomy, markets, and government policies. The industry has displayed resilience and adaptability when faced with changing and often adverse market conditions. Forest products industries have a history of success despite the challenges of cyclical market upheaval. Previous analyses have contributed to greater understanding of the dynamic nature of forest industries. These works form the groundwork for this study and are discussed next.

3. Literature Review

Much work has been done previously to analyze forest products and other industries in the United States, the Pacific Northwest, and internationally. Production function estimation is a standard technique employed by applied economists to study the production structure of industries and estimate response to market conditions or policy shifts. More recent studies employ duality theory, which allows estimation of dual cost or profit functions. This section begins with a summary of duality theory and functional forms that provide the theoretical backbone for production analysis. Then, previous empirical work developing models of the lumber manufacturing industry in the United States, the Pacific Northwest, and western Washington are discussed, followed by studies from other industries and regions. The last section summarizes different methods used to model technical change and to construct capital data series.

3.1 Duality Theory

Traditionally, forest products sector econometric models have either directly estimated an industry production function or specified a dual cost or profit function from which input demand and output supply equations are derived. The resulting parameter estimates are used to quantify the relationship between inputs and outputs through calculations of substitution and price elasticities as well as measures of returns to scale of operation and technological change.

Econometric modeling techniques can capture the adjustment process that occurs as industries alter input usage and input-output mix to adapt to changing market conditions. Generally there is some ability to substitute one input for another, or inputs may be complementary. Thus, increased scarcity of one input may cause significant changes in the demand for other inputs. Duality theory can be applied to systems of equations estimation procedures to represent these interrelationships and is well suited to modeling firm response to changing input and output prices, technological innovation, and policy restrictions. 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 using the production function directly; it allows use of more complex functional forms which impose fewer maintained hypotheses on the structure of production.

Duality theory is a relatively recent development in neoclassical economic analysis. Hotelling (1932) pioneered the use of duality in economics by applying it to consumption theory. Shepherd’s text (1953) developed the fundamental methods for applying duality theory to production decisions. 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. 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. This choice of approaches has been called duality theory's greatest contribution to empirical work (Chambers 1982). By the early 1980s, studies employing duality theory to production had become mainstream in the literature of a variety of applied fields.

Nerlove (1963) was the first to apply duality theory to econometric cost analysis in his study of the U.S. electric power industry. Using a Cobb-Douglas function, Nerlove used the duality between production and cost functions to model output as a function of capital, labor, and fuel costs. This study represented a major breakthrough in empirical production analysis and econometric methods. Nerlove’s study was subsequently updated later by Christensen and Greene (1976) who used a flexible translog functional form and simultaneously estimated the factor demand equations and the cost function. Agricultural production was another area to see concentrated empirical use of dual functions; Binswanger (1974) first used a cost function to analyze technical change and factor substitution in U.S. agriculture. Productivity studies of the lumber manufacturing sector appeared in the literature in 1967 when William McKillop performed the first econometric study of supply and demand for forest products in the United States. Applications of duality theory in forest products industries largely occurred after 1980.

3.2 Functional Forms

The form of any industry production function is not observable; empirical economic research has led to the development of several possible functional forms. Early efforts to estimate production structure in industries relied upon relatively simple forms of the production function. The Cobb-Douglas production function is one example. Developed in 1928, the Cobb-Douglas predated duality theory and was introduced into the economics literature in the course of an empirical study examining the problem of relating inputs and output at the national level (Cobb and Douglas, 1928). Since then, the Cobb-Douglas function has been the most commonly used function in the specification and estimation of production in empirical studies. It is attractive due to its simplicity; the logarithmic nature of the production function makes econometric estimation of the parameters a simple matter. Later application of duality theory resulted in the Cobb-Douglas cost function. Yet as Yin (2000) points out, this function may be criticized for its restrictive assumptions about the nature of the production technology, such as unitary elasticity of substitution and constant returns to scale and input elasticities.

As common as the Cobb-Douglas has been, surprisingly few studies have applied a dual Cobb-Douglas cost function to examine the production structure in forest industries. The only studies found pertain to the effects of unions on western sawmill productivity (Mitchell and Stone, 1992), differences in U.S. regional construction costs (Johannes, Koch, and Rasche, 1985), and cyclical dumping of Canadian pulp and paper into European markets (Brannlund and Lofgren, 1995). Buongiorno and Gilless (1980) used a Cobb-Douglas production function to model international pulp and paper prices. This lack of Cobb-Douglas applications in lumber manufacturing studies motivated its use here.

The criticism that early functional forms placed severe limitations on model estimation led to the development of flexible functional forms which incorporate fewer maintained hypotheses about the nature of the production technology. The transcendental logarithmic (translog) (Berndt and Christensen 1973), the generalized Leontief (Diewert 1971) and the generalized Box-Cox (Berndt and Khaled 1979) all permit empirical testing of the nature of the effects of factor substitution, returns to scale, and technical change. By far the most widely used cost function in empirical work, in both single- and multiple-output contexts, has been the translog. The translog form can be used for testing hypotheses involving returns to scale, separability of inputs, and the degree of input substitutability. This form has both linear and quadratic terms with an arbitrary number of inputs (Berndt and Wood, 1975). The translog model differs from the Cobb-Douglas model in that it relaxes the Cobb-Douglas assumption of unitary elasticity of substitution (Greene, 2003).

Literature for the forest products industry abounds with production studies based on the translog production and dual cost function. This section highlights previous empirical analyses performed on lumber manufacturing in the United States, including studies at the national, Pacific Northwest regional and Washington state level. Studies from other industries and regions follow.

3.3 Empirical Studies of Lumber Manufacturing

United States--Stier (1980a) was the first to use the dual translog cost function to estimate the production technology in ten U.S. forest products industries, including sawmills and planing mills (SIC 242). Using two inputs, capital and labor, and a time trend variable over the period 1958-1974, Stier estimated the parameters of one cost share equation rather than estimating the parent and cost share equations simultaneously. Substitution between capital and labor in sawillls was highly inelastic, indicating an inability to adjust to changing relative prices in the short run. This limitation was also reflected in the inelastic cross-price demand for capital and labor. Results indicated that technological progress in sawmills was based upon labor-saving efficiency gains expected to have serious consequences for labor in the sawmill and planing mill industry (SIC 242), already facing declining employment opportunities.

Stier (1980b) examined technological adaptation to resource scarcity in the U.S. lumber industry (SIC 242) from 1950 to 1974. The analysis included a translog average cost model with three inputs, capital, labor, and wood, and a time variable to proxy technical change. He found that technological progress in sawmills had been labor-saving, capital-using, and wood-neutral.

Abt (1987) was the first study to compare regions within the U.S. by performing an analysis of regional differences in lumber production structure from 1963 to 1978. A restricted translog cost function with labor and sawlogs as variable inputs and capital as quasi-fixed was estimated for three lumber producing regions, the Pacific Northwest, the Southeast, and the Appalachian hardwood region. In the restricted approach, variable inputs sawlogs and labor are assumed to adjust to their cost-minimizing level given variable factor prices, the state of technology, and the level of capital stock. Technology was estimated with a time trend variable. Cost function parameter estimates were used to decompose trends in factor demand and significant regional differences were found. The PNW showed labor and capital use was highly sensitive to own- and cross- price changes and increases in capital stock were associated with decreased sawlog demand and almost no effect on labor demand. Results were calculated with constant returns to scale restrictions imposed, making comparisons with unrestricted models somewhat dubious.

Abt *et al.* (1994) applied nonparametric superlative index techniques within a translog cost function to measure productivity growth in the sawmilling industries of the United States and Canada. Six geographic regions were examined: British Columbia (Coast and Interior), Ontario, Quebec, U.S. South, and U.S. West. The results indicate significant adjustment of resources both within and across regional industries over time. Over the long-term, labor experienced the greatest productivity gains with 3-4 percent annual growth. This result likely reflected significant increases in capital stock throughout North America.

Nagubadi *et al.* (2004) used a translog cost model to address substitutability among imported and domestically produced lumber by species within the context of the softwood lumber trade dispute between United States and Canada. Monthly data from Jan. 1989 to July 2001 were gathered for five inputs: softwood species used in softwood-utilizing industries, capital, labor, energy, and other materials. Results showed the spruce-pine-fir lumber species group mainly imported from Canada was largely unrelated to domestically produced treated southern yellow pine, Douglas-fir, and other species groups. Canadian s-p-f was a substitute for untreated southern yellow pine and engineered wood products.

Pacific Northwest--David Merrifield (1983) developed the first market model for the Pacific Northwest forest products industry incorporating a flexible form production function into a system of supply and demand equations. He used a translog production function rather than the dual cost function, arguing that output was endogeneous. The model was specified with softwood lumber and plywood outputs and labor, stumpage, and capital inputs with data from 1950 to 1976. The model was used to test the effects of exogenous demand and supply shifts on variables endogenous to the PNW forest products industry.

In a related publication, Merrifield and Haynes (1984) used an equilibrium model of output and factor markets to calculate the effects of demand and factor supply shifts on output, factor prices, and employment in the Pacific Northwest forest products industry. They studied the linkage between factor and product markets for the aggregated PNW lumber and plywood industry. The link between output and factor levels was provided through the three-input (labor, stumpage, and capital) translog production function described above. The model did not yield satisfactory results in terms of correct signs and significance of estimated coefficients of capital supply equation.

A subsequent publication from Merrifield and Haynes (1985) employed the dual translog total cost function to study the structure of lumber and plywood production after separating the Pacific Northwest into two regions, eastside and westside. For the period from 1950 to 1979, they disaggregated capital into structures and equipment but were unable to detect any significant effect of technical change on demand for production inputs.

Washington--Three previous Ph.D. dissertations have been written from studies that systematically analyzed the lumber industry in Washington. Cardellichio (1986) was the first to employ production theory in his analysis of the economics of softwood lumber production in Washington. He used a pooled cross-section and time series data set with biennial mill-level observations from 1972 to 1984; his data were obtained from the Washington Mill Survey. He used a constant elasticity of substitution (CES) production function in a fixed effects panel data model with sawlogs, labor, and capital inputs, fixed capital services, and constant returns to scale assumptions. Results published subsequently showed mill capacity, mill age, headrig type, and log diameter were key variables influencing log use (Cardellichio, 1989). He could not rule out the hypothesis that lumber production was a fixed factor proportion production process; a short time frame limited the success of his model estimation.

Stevens (1991) aggregated mill-level biennial WADNR survey data to the county level to explain disproportionate job impacts observed between skilled and unskilled western Washington sawmill workers over the period 1980-1988. Stevens used a normalized quadratic profit function with energy, unskilled labor, and sawlogs variable inputs, skilled labor and capital quasi-fixed inputs, a time trend for technological progress, and fixed effects for underlying differences in production processes. The timeframe encompassed the decade of the 1980s, a recessionary period with negative profits and many mill closures. With only five time-series points and 16 cross-sectional county groups, the author acknowledged that the results could benefit from additional time-series observations. His analysis was published subsequently (Stevens, 1995).

Weiner (1996) analyzed the economic behavior of Washington's lumber industry for the period from 1968 to 1990. Biennial DNR mill survey data were used and aggregated to the state level. Using a normalized quadratic profit function specification, he explicitly modeled technological change using three variables, the number of sawmills operating large circular saws, average eight-hour milling capacity, and number of mills operating a chipper. Incorporating mill technology variables was hypothesized as an improvement over traditional techniques relying on a time trend. Biennial DNR mill survey data were again used and aggregated to the state level; values for years when data were unavailable were interpolated. The author echoed Stevens' hope that subsequent data would extend the time horizon to incorporate market changes occurring in the 1990s.

The apparent lack of recent research into sawmill structural changes in Washington was unexpected given the volatile conditions facing the industry since the early 1990s. The present study analyzes the western Washington lumber industry using predominantly mill level data from 1972 to 2002 aggregated to the county level. This study differs from Cardellichio because it employs a longer time frame with a greater number of degrees of freedom for statistical analysis. It expands on Stevens and Weiner by examining periods of sector expansion and contraction. It is the first known study comparing the Cobb-Douglas and translog cost functions to analyze western Washington lumber manufacturing, and the only study to report results at the regional and county level over time.

3.4 Other Regions and Industries

Canada--The production structure of the Canadian lumber industry has received considerably more attention from economists. Production studies of the Canadian lumber industry employed both cost and profit functions. Studies using cost functions include Banskota, Phillips and Williamson (1985), Martinello (1985), Nautiyal and Singh (1985), Singh and Nautiyal (1986), Martinello (1987), Meil and Nautiyal (1988), and Puttock and Prescott (1992). The majority of these studies were conducted in the 1980s, meaning their conclusions are based upon data containing no information from the 1990s. Recent studies show there has been renewed interest in the industry since 2000 (Latta and Adams, 2000; Wiilliamson et al., 2005; Nagubadi and Zhang, 2006). In most cases, data for the industry was taken from Statistics Canada for SIC code 2512, sawmills and planing mills. Output has mostly been defined as softwood lumber or lumber and chips, but some studies have included hardwoods. Inputs include wood, materials, capital, labor, and energy. Most studies used a time trend to represent technology and report substitution and price elasticities, economies of scale, and technology change.

Banskota, Phillips and Williamson (1985) examined factor substitution and economies of scale in the Alberta sawmill industry using cross-section data collected for 83 Alberta sawmills for the year 1978. Allen substitution elasticities, own- and cross-price demand elasticities, and economies of scale were calculated using a nonhomothetic translog cost function model with four factor inputs: labor, capital, wood, and energy. No attempt was made to model technological change. Restrictions including a homothetic and homogeneous cost function, unitary elasticity of substitution, and Cobb-Douglas forms were tested and rejected. All own-price elasticities were negative, energy had the most elastic demand; wood demand was the least elastic. Energy, capital, and labor were highly elastic substitutes. Wood and capital were complements and wood and labor were weak substitutes, suggesting difficulty mitigating wood cost increases. Economies of scale calculations for six mill sizes showed a positive association between larger sawmills (higher output) and scale economies.

The same year, Martinello (1985) estimated factor substitution, technical change, and returns to scale in three Canadian forest industries, including sawmills and shingle mills, with annual data from 1963 to 1982. He used an unrestricted translog cost function with capital, labor, energy and wood inputs and a time variable to represent technology. Sawmills showed increasing returns to scale (1.11) and Allen substitution between labor, energy and wood was highly elastic, as was energy own-price elasticity. Wood prices had the greatest impact on total costs. He reported a small negative trend (0.4% per year) in total factor productivity and technical change was capital- and energy-using and labor- and wood-saving.

In a later study Martinello (1987) employed the same technique to examine mill structure in coastal and interior British Columbia. Data were aggregated to the four-digit level (SIC 2512 instead of SIC 251), the data period was a few years shorter (1963-1979), the energy input was dropped, and capital services were calculated differently than Martinello 1985. Returns to scale generally agreed with the previous study of Canada as a whole, with values of 1.22 and 1.00 for coast and interior, respectively. Capital and labor were very elastic substitutes and capital had the greatest own-price demand elasticity in both regions. Technical change was capital-using, labor-saving, and wood-neutral in coastal mills and capital-using and labor- and wood-saving in interior mills. 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 noted that declining size and quality of timber in the Interior region had stimulated investment in mills capable of processing large volumes of smaller logs, whereas the Coastal industry had not yet made the transition to a second-growth timber resource. In general, results for interior mills agreed more closely to results for Canada as a whole than results for coast mills.

Nautiyal and Singh (1985) analyzed lumber production in Canada from 1965 to 1981 using a restricted (homothetic and homogeneous) translog cost function with inputs capital, labor, energy and roundwood and a time trend for technological progress. They found large economies of scale, but made no attempt to analyze economies of scale by firm size. Capital and energy demand were both highly own-price elastic and capital was the most easily substituted input, especially for energy. Like Martinello (1985), average production costs were most sensitive to roundwood price, then by labor price; unlike Martinello, they found no evidence of technical progress.

Singh and Nautiyal (1986) studied the long-term productivity and demand for inputs capital, labor, energy and wood in the Canadian lumber industry from 1955 to 1982 with a translog cost function and a time variable to represent technology change. They applied a cross-stock adjustment process in the share equations to calculate long-run least-cost amounts of the inputs to test rates of factor use adjustment. Deviations of the observed amounts of each input from their least-cost levels were computed to determine the degree of allocative inefficiency.

Meil and Nautiyal (1988) estimated a restricted translog variable cost model applied to four regions (B.C. coast, B.C. interior, Ontario, and Quebec) to analyze interregional Canadian softwood lumber production structure and factor demand from 1968-1984. This was the first Canadian study to disaggregate the Canadian sawmill industry by region and by mill size. Firms were classified into four size groups based on number of employees and a time trend was used for technological progress. They found that different regions and different mill sizes within a region displayed different production behavior. Energy had the highest substitution elasticity in all regions and all mill sizes. Wood was the least substitutable input in all cases except small mills in Quebec. Larger mills showed the greatest labor-saving technological change; mid-sized mills exhibited the largest returns to scale. Technical change bias was labor-saving and material- and energy-using in almost all cases. Data suggest that small mills were leaving the industry in some regions and production capacity was increasingly concentrated in larger mills.

Puttock and Prescott (1992) used a translog cost function to model the southern Ontario hardwood sawmilling industry. Analysis of pooled data revealed that a nonhomothetic translog cost function was an appropriate representation of the industry. Total cost was specified as a function of mill output; the input prices for wood, labor, and energy; and a measure of mill capacity. All own-price elasticities were negative in sign. All input pairs were found to be substitutes, with labor and energy displaying the strongest substitution relationship. There were economies of scale yet to be exploited by sawmills producing less than 16 million board feet of lumber annually; scale economies were fully exhausted for mills with a greater annual output.

Later studies of Canadian lumber production Constantino and Haley (1988), Baker (1990), Adams and Haynes (1996), Bernard et al. (1997), Latta and Adams (2000) were performed using profit functions. Nonetheless, the most recent study of the Canadian lumber industry appeared in Nagubadi and Zhang (2006). They used a translog cost function over the period from 1958 to 2003 to study the production structure and input substitution in Canadian sawmills and wood preservation industries. They used seven inputs: production labor, nonproduction labor, machinery and equipment capital, plants and structures capital, fuels energy, electric power, and materials. Output was the sum of six products: softwood lumber, hardwood lumber, wood chips, wood preservation products, wood ties, shingles, shakes, and others. A time trend was used for technological change.

The Lake States--McQueen and Potter-Witter (2006) estimated sawmill productivity, technological change and factor demand in the Lake States. A translog variable cost function was estimated for the industry in Michigan, Minnesota, and Wisconsin using pooled time-series data for the period 1963-1996. Production inputs were labor, materials, and capital; technical change was assumed Hicks-neutral. The three inputs were inelastic substitutes; own- and cross-price demand elasticities were all inelastic. The industry exhibited increasing returns to scale and positive technical change. Total factor productivity increased by 0.69 percent annually over their data period.

Logging-The translog cost function has been used to study the logging industry in the U.S. and Canada. Smith and Munn (1998) conducted a regional cost function analysis of the U.S. logging industry. Translog cost functions with two variable inputs, labor and capital, were estimated to compare the logging industry in the Pacific Northwest and Southeast from 1963 to 1992. A time trend was used to model technical change. The parent cost function and capital share equation for each region were estimated and tests suggested the regions were significantly different. The industry in both regions was capital-using over the data period. Labor and capital were inelastic substitutes in each region, but more elastic in the Southeast, suggesting the industry in the Southeast was better able to adjust to market changes.

Kant and Nautiyal (1997) employed a translog cost function to create an unrestricted benchmark model of the Canadian logging industry from 1963 to 1992. They sequentially estimated and compared nine more restricted models: Hicks neutral technology, no technical change, homothetic, homogeneous, unitary elasticity of substitution, homothetic and unitary elasticity of substitution, homogeneous and unitary elasticity of substitution, homogeneous and Hick's neutral technology, and homogeneous and no technical change. One model was then selected using likelihood ratio testing. From the parameters estimated from that model, they calculated elasticities of substitution, rate of technical change, and the total factor productivity growth.

Pulp and paper--Pulp and paper industries have also been examined. DeBorger and Buongiorno (1985) developed indices of productivity growth for the paper and paperboard (SIC 2621 and 2631) industries using data from 1958 to 1981. They used a variable translog cost function with variable inputs labor, energy, and materials, quasi-fixed input capital, a time trend to proxy technology, and homotheticity and homogeneity constraints imposed. Both industries had short-run economies of scale but long-run diseconomies. Demand for variable inputs was price inelastic; energy demand was most elastic of the three. Cross-price and substitution elasticities suggested substitution potential between energy and materials and between labor and materials but no trade-offs between labor and energy. Average rate of growth in the paper industry was much higher than paperboard; both had significant labor-saving and energy-using biases.

Stier (1985) used a translog cost function to investigate factor substitution, returns to scale, and biased technological progress for the aggregate U.S. pulp and paper industry over the period 1948-76. The results were consistent with cost minimizing behavior on the part of firms, and indicated that in the short-run increases in the prices of capital, labor, or wood inputs would drive up commodity price. Expansion of aggregate output at constant factor prices would lead to declining costs as a result of economies of scale. This feature of production led to a relatively concentrated industry characterized by very large plants. The main vehicle for achieving cost savings was through labor-saving technological progress and a wood-using bias was found.

Quicke et al (1990) examined the U.S. paper industry (SIC 262) from 1958-1985 using very similar models and data to DeBorger and Buongiorno (1985). The study reported substantial rates of increase in total factor productivity, ranging from 2 to 4 percent per year depending upon the measure used. While both also found significant labor-saving and energy-using biases, Quicke et al. also reported a significant material-saving bias.

McCarthy and Urmanbetova (2006) performed the most recent analysis of structural changes in the U.S. pulp and paper industry. Based on aggregate data from 1965-1996, they estimated a translog cost function for the industry's short-run costs. This is one of the few studies to adjust for serial correlation. They found the industry operated at slightly increasing returns to capital utilization, labor and energy were complements in production, and materials were substituted for other production inputs. Technological progress generated an average 0.037 percent reduction in annual operating costs but the effect was much larger early in their data period. Estimated marginal costs approximated average operating costs until 1981; afterwards marginal costs significantly diverged from average operating costs.

3.5 Technological Change and Capital Series

In general, the studies summarized above used a similar methodological approach to analyze production structure. However, modeling technological change and developing good measures of capital inputs have challenged economists for decades. Researchers have attempted a variety of techniques to estimate technological change and create capital data series. These techniques are discussed next.

Technological change--In the standard technical change model, it is assumed that a time trend can be used as a proxy for technical change. This is the most widely employed approach to measuring technical change in applied research. Studies by Singh and Nautiyal (1984), DeBorger and Buongiorno (1985), Martinello (1985, 1987), Nautiyal, and Singh (1985), Stier (1985), Merrifield and Singleton (1986), Meil and Nautiyal (1988), Meil et al. (1988), Stevens (1991, 1995), Kant and Nautiyal (1997), Smith and Munn (1998), Baardsen (2000), Latta and Adams (2000), Stordal and Baardsen (2002), McQueen and Potter-Witter (2006), and Nagubadi and Zhang (2006) have all employed a time trend to measure technological change in various forest industries.

The time trend model has several drawbacks (Lundmark, 2005). The time trend assumes the technical change occurs linearly at a constant annual rate; empirical evidence suggests that technical change is often "lumpy", occurring in discrete intervals rather than in a continuous smooth fashion over time (Cardellichio, 1986, 1989). Moreover, the time trend is often correlated with output and price variables, leading to biased regression coefficients. These shortcomings are acknowledged in most studies. Nautiyal and Singh (1985) defend incorporating the time trend when the aim is to test for the existence of technical change and its significance on the cost of production; in these cases, objections to the constant rate assumption are less serious.

Efforts to improve on the time trend method were made by Cardellichio (1986, 1989, 1990), Weiner (1996) and Lundmark (2005). Cardellichio represented the state of technology by two mill specific variables, mill age and type of headrig. He also used variables to control for changing wood quality, including species and type of wood sawn (old growth, utility, or dead) as well as geographic region and mill capacity. Cardellichio's model 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 log price an insignificant variable.

Weiner used a profit function to model Washington's lumber industry and explicitly included technology and log quality variables. The variables he used were type of head-rig, log size, and presence of a chipper. His results indicated that technology variables had an impact on lumber manufacturing employment rates.

Lundmark compared three approaches to measure technical change in the Swedish newsprint industry, a Tornqvist index, standard time trend, and a general index. Results indicated significant differences between the three with the time trend providing the most conservative estimate of technical change. He also identified the main determinant of technical change in Swedish newsprint industry as capacity utilization, but regulatory intensity and output prices were also important.

Capital--Many authors have reported problems estimating capital inputs in forest sector industries. The difficulty lies in finding adequate measures of capital stock and rental or user price series from published sources. Researchers have tried a multitude of techniques to overcome the difficulties associated with measuring capital.

The perpetual inventory method developed by Christensen and Jorgenson (1969) has been used extensively for constructing capital stock series in forest products studies, including Stier (1985), Stevens

(1991, 1995), Smith and Munn (1998), and McQueen and Potter-Witter (2006). Stevens used a unique method to measure quantity of capital. He employed the Christensen and Jorgenson perpetual inventory method in a three step process of first determining initial capital stock, adding or subtracting changes in stock levels, and last calculating the net changes to stock including depreciation. User cost of capital was subsequently calculated from these capital stock values and the annual assessed value of additions or subtractions of capital equipment and machinery. These values were obtained by visiting each County Assessor's office to obtain the total assessed value of firms, capital equipment, and machinery.

Capital stock estimates were based on measures of industry capacity in DeBorger and Buongiorno (1985), Latta and Adams (2000), and Helvoigt (2006), representing maximum service output of the stock.

Stier (1985) created a capital stock series for U.S. pulp and paper and then calculated the price of capital by dividing gross quasi-rent (value-added minus payroll from the Annual Survey of Manufacturers) by capital stock. This technique was followed by Smith and Munn (1998) and McQueen and Potter-Witter (2006).

The opportunity cost principle was used in Singh and Nautiyal (1984), Nautiyal and Singh (1985), Meil and Nautiyal (1988), and Kant and Nautiyal (1997) to calculate the price of capital in Canadian lumber and logging industries. Assuming the rate of return on capital was the same as its opportunity cost, capital price was calculated as the rate of return on fixed assets. Net profit after tax and net fixed assets were obtained from Statistics Canada and their ratio taken as a proxy for the rental price of capital.

Martinello (1987) constructed a capital stock series using two-digit aggregate capital stocks for the entire the British Columbian wood products industry. Those aggregate data were combined with disaggregated data on energy consumption to produce price and quantity series for capital services. The flow of capital services was assumed to be a constant proportion of the capital stock. Martinello (1985) and Merrifield and Haynes (1983, 1984) also assumed that payments for capital services were proportional to the value of capital stock.

The 1984 analysis led to lackluster results for capital services, Merrifield (1985) devised another method to construct capital estimates. He compared two methods for generating capital price and capital stock series for structures and equipment in U.S lumber and plywood industries from 1950-1979. The residual (or quasi-rent) approach was compared against two methods using implied service life and capacity depreciation patterns to derive implied rental prices and capital stock series for equipment and structures.

Merrifield and Singleton (1986) tried again, using data obtained from the Census of Manufactures and Annual Survey of Manufactures to construct a nominal rental cost of capital series using the formula:

$$u_K = \frac{q_K(R+\sigma)}{(1-tax)}$$

where q_K is the acquisition cost of one dollar of capital stock as measured by the implicit price deflator for fixed investment of structures and producers durable equipment, R is the prime rate, σ is the industry capital depreciation rate, and *tax* is the marginal corporate tax rate from the IRS.

Nagubadi and Zhang (2006) used capital stock data from Statistics Canada and computed service price of capital by adding the bond interest rate on total capital stock, deprecation on machinery and equipment based on 12 year life (8.33 percent) and depreciation on plants and structures based on 20 year life (5 percent).

Norwegian researchers Baardsen (2000) and Stordal and Baardsen (2002) measured real capital in machinery and buildings at 70 percent of recorded fire insurance values divided by the price of capital, which was proxied by a building cost index. Rental values for machinery and buildings were then calculated as the building cost index multiplied by the sum of a discount rate from Norwegian savings banks and a rate of replacement. Rental of capital services were then calculated as a weighted average of the machinery and building rental values.

One way of avoiding estimation of capital costs is to use variable cost models with capital inputs as fixed or quasi-fixed. This method is consistent with a short-run approach to production where mills are able to adjust some production inputs quickly while others take time. This only requires data for the quantity of capital or capital stock, rather than quantity and price data. Many production studies of forest industries, including Merrifield and Singleton (1986), Abt, (1987), Meil and Nautiyal (1988), Meil et al. (1988), Stevens (1991, 1995), Weiner (1996), Latta and Adams (2000), and Lundmark (2005) have used this approach. While this method is appropriate for modeling industrial behavior in the short-run, capital is allowed to vary here owing to the long-run nature of the thirty-year biennial data set.

4. Production Theory

Mill owners produce lumber by transforming logs, labor and capital inputs into output. Over time, changes in technology, input and output prices, and other factors influence production decisions. This process can be modeled mathematically using a production function or dual cost function approach. Both are standard techniques employed by applied economists to analyze production structure and estimate response to changing market conditions.

A number of assumptions are imposed on producer and market behavior *a priori*:

- Firms produce a single output and maximize profits
- Firms purchase or rent profit-maximizing levels of production inputs
- Markets for output are competitive; firms have no control over output price
- Firms have variable techniques of production and can choose from various input combinations to create the same output.

The production process can be conceptualized as a production function. A production function is a mathematical representation of the relationship between inputs and outputs, summarized as:

$$Y = f(X_1, X_2, ...X_n, T),$$

where Y is output, $X_1, X_2, ..., X_n$ are factors of production, and T represents technology. The function f is the numerical rule that transforms levels of inputs into output (Silberberg and Suen, 2001). Using the production function approach, firms choose the level of output as well as the quantity of factor inputs that maximize profits. Arguments are in quantities.

Duality theory developed by Samuelson (1947) and Shepherd (1953, 1970) provides the theoretical foundation for estimating production parameters by a corresponding cost function. In cases where output price and quantity are determined exogenously, revenue is essentially fixed. Profits are maximized by minimizing the total cost of producing a given output level. Thus, profit maximization implies cost minimization (Silberberg and Suen, 2001).

This study uses the cost function approach for estimating production structure. Factor prices are assumed to be exogenous and the firm chooses input levels to minimize the cost of producing a given level of input. The generalized cost function is represented by

$$C = C^*(Y, P_1, P_2, ..., P_n, T)$$

where C is the total cost associated with the set of cost minimizing input levels, Y is output, $P_1, P_2, ..., P_n$ are the set of factor prices, and T represents the state of technology.

The firm's problem is to find the factor combination that produces a given output Y at the lowest total cost. Thus, costs are constrained by the production technology available to the firm. In the two input case, the objective function facing a profit maximizing firm is:

$$\min C = P_1 X_1 + P_2 X_2$$

subject to

$$Y^* = f(X_1, X_2, T)$$

where

C = total cost,
X_1, X_2 = factor input quantities,
P_1, P_2 = factor input prices,
Y^* = output, and
$f(X_1, X_2, T)$ = production function with technology variable.

The firm seeks to use its production technology (represented by the production function) to combine factors X_1 and X_2 at the lowest total cost while still producing output Y^*. The necessary first order conditions for a minimum are derived by setting the first partial derivatives equal to zero. Setting up the Lagrangian form with λ as the Lagrangian multiplier:

$$L = P_1X_1 + P_2X_2 + \lambda(Y^* - f(X_1, X_2, T)).$$

The first order conditions are:

$$\frac{\partial L}{\partial X_1} = P_1 - \lambda f_{X_1} = 0$$

$$\frac{\partial L}{\partial X_2} = P_2 - \lambda f_{X_2} = 0$$

$$\frac{\partial L}{\partial \lambda} = Y^* - f(X_1 X_2, T) = 0.$$

The sufficient second-order conditions for a minimum require that the bordered Hessian matrix of second partial derivatives of the Lagrangian with respect to X_1, X_2, and λ is negative:

$$H = \begin{pmatrix} -\lambda f_{X_1X_1} & -\lambda f_{X_1X_2} & -f_{X_1} \\ -\lambda f_{X_2X_1} & -\lambda f_{X_2X_2} & -f_{X_2} \\ -f_{X_1} & -f_{X_2} & 0 \end{pmatrix} < 0.$$

With only two inputs, the production decision can be represented graphically. Figure 19 contains isocost lines *C1* and *C2* connecting the two axes; these show all combinations of *X1* and *X2* with the same total cost. The curve, or isoquant, represents all combinations of factors *X1* and *X2* that produce a given level of output *Y*. For a given isoquant, total revenue is fixed, but each possible combination of inputs produces a different level of cost, reflected in the isocost lines. The cost-minimizing producer operates at the point of tangency where the slope of an isocost line equals the slope of the given Y isoquant. This tangency point is point A in Figure 19, which represents the cost minimizing factor input combination $X1_a$ and $X2_a$.

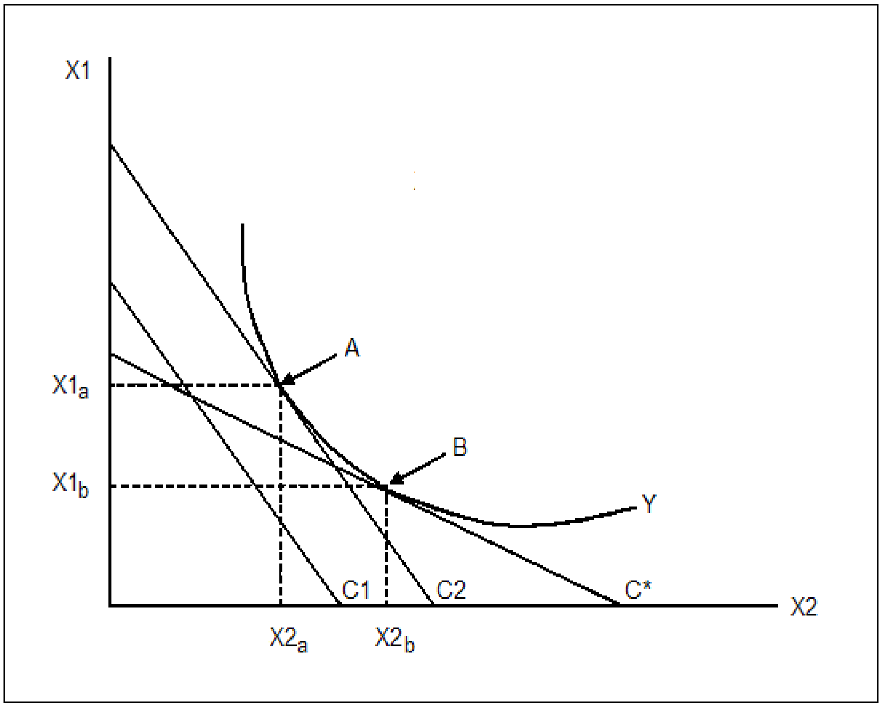

Figure 19. The cost minimizing production decision

Figure 19 also shows how cost minimizing firms substitute between factor inputs in response to relative price changes. If the price of *X1* rises and *X2* falls, the slope of the isocost line changes from *C2* to *C** and point A no longer represents the best input choice. The cost-minimizing producer responds to the price change by choosing more *X2* and less *X1* , resulting in a move to point B at the tangency point of isocost line *C** and isoquant *Y*. The new choice of inputs, $X1_b$ and $X2_b$ is quite different with more *X2* and less *X1* used than before (Silberberg and Suen, 2001).

The first- and second-order conditions for a minimum define the curvature properties of the underlying production structure. Isoquants must have a negative slope and must be convex to the origin. The slope of an isoquant corresponds to the marginal rate of technical substitution; a negative slope reflects the diminishing ability to substitute between inputs. In addition, convexity of input combinations is required because of the law of diminishing marginal productivity. Diminishing marginal productivity implies that greater use of any one input, holding all other fixed, leads to diminishing increases in output (Chambers, 1988). These requirements must hold for the cost function to be well-behaved, meaning that empirical results agree with underlying economic theory of profit maximizing behavior.

Additional assumptions are often asserted on the cost function. These assumptions are maintained hypotheses about the geometry of the function that can be tested or imposed *a priori*:

- $C(Y, P_1, P_2, ..., P_n, T) > 0$ for $P_n > 0$ and $Y > 0$ Costs are non-negative, real-valued, and single-valued for all non-negative and finite P_n and Y.

- $C(0, P_1, P_2, ..., P_n) = 0$ No costs are incurred when firms stop production.

- If $Y' \geq Y$, then $C(Y', P_1, P_2, ..., P_n, T) > C(Y, P_1, P_2, ..., P_n, T)$ Additional units of output increases cost (monotonic in Y).

- If $P_n' \geq P_n$, then $C(Y, P_1', P_2', ..., P_n') > C(Y, P_1, P_2, ..., P_n)$ Increasing prices of inputs increases cost (monotonic in *P*).

- $C(Y, \lambda P_1, \lambda P_2, ..., \lambda P_n) = \lambda C(Y, P_1, P_2, ..., P_n)$ Costs are homogeneous of degree one in prices.

- $C(Y, P_1, P_2, ..., P_n, T)$ is continuous and twice-differentiable in prices.

- $C(Y, P_1, P_2, ..., P_n, T)$ is concave in prices.

According to Shephard's lemma (1953), if the cost function is differentiable, the cost minimizing factor demand of the i^{th} input is the partial derivative of the cost function with respect to that input's price:

$$\frac{\partial C(Y, P_i, P_j, ..., P_n, T)}{\partial P_i} = X_i \ .$$

The resulting X_i is the demand for factor *i* given the other factor prices and output level. Thus, by Shephard's lemma, factor demand equations for each production input can be derived directly from the cost function. In the case of a logarithmic cost function,

$$\frac{\partial(\ln C)}{\partial(\ln P_i)} = \left(\frac{\partial C}{\partial P_i}\right)\left(\frac{P_i}{C}\right) = \frac{P_i X_i}{C} = M_i$$

where M_i is the share of factor *i* in total cost. This computational ease attests to the utility of the cost function approach in applied production analysis.

For a well-behaved cost function, factor demand equations are homogeneous of degree one with respect to factor price effects. A function $f(X_1, X_2, ...X_n, T)$ is homogeneous of degree r if:

$$f(tX_1, tX_2, .., tX_n) \equiv t^r f(X_1, X_2, .., X_n) \, .$$

In the case where a production function is homogeneous of degree one, r = 1, so:

$$f(tX_1, tX_2, .., tX_n) \equiv tf(X_1, X_2, .., X_n) \, ;$$

increasing all inputs by the same amount leads to an identical increase in output. Homogeneity of degree one, or linear homogeneity, implies that marginal productivity of the factor inputs remains constant. Only relative price changes matter to production decisions.

Homogeneous functions (of whatever degree) are special cases of a more general class of functions known as homothetic functions. A function *F* is homothetic if it is a monotonic transformation of a homogeneous function *f*, such as:

$$F(f(X_1, X_2, .., X_n, T)) \, .$$

Figure 20 is a representation of a homothetic production function. Homothetic production technology is characterized by production isoquants that are radial expansions of each other. This linear expansion path means that the slope of any ray out of the origin and the isoquants are equal (Silberberg and Suen, 2001). Increasing production increases demand for inputs but does not change the relative factor mix, implying fixed factor production. Thus, homotheticity implies that the marginal rate of substitution is constant for constant factor ratios. In Figure 20, Y1 and Y2 are homothetic production functions; the slopes along the ray are equal and the proportion of X1 and X2 utilized in production remains constant (Silberberg and Suen 2001).

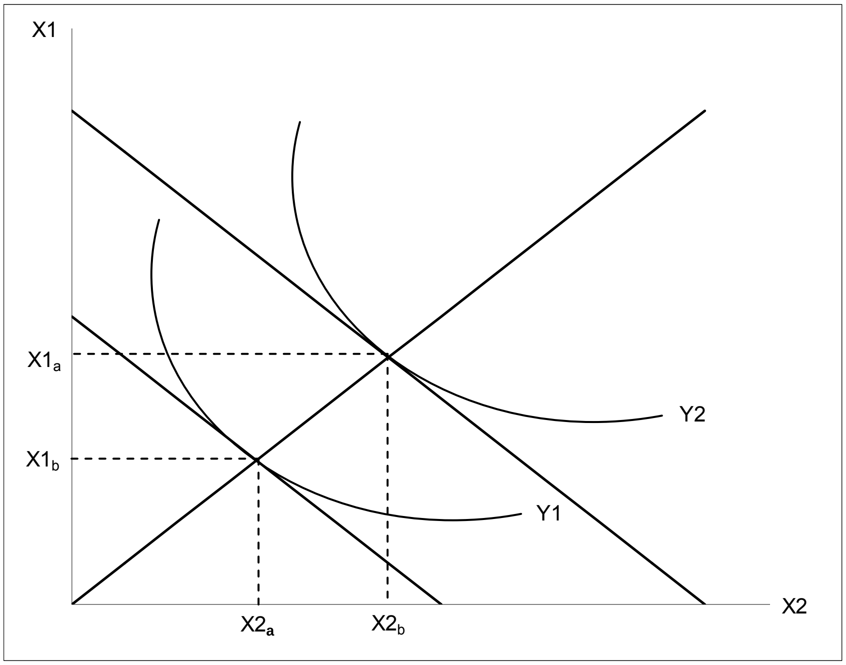

Figure 20. Homothetic production functions

Additional assumptions are often made about the symmetry of coefficients. The cross-partial derivatives of the Hessian matrix are often assumed to be symmetric, meaning that $f_{X_1,X_2} = f_{X_2,X_1}$. This assumption is based on Young's theorem, which states that if $Y = f(X_1, X_2, T)$ has second-order partial derivatives that exist and are continuous, then $f_{X_1,X_2} = f_{X_2,X_1}$.

4.1 Economies of Scale

Many models of producer behavior make or test assumptions about returns to scale. The cost function recovers scale relationships because costs are influenced by the scale of production (Chambers, 1988). Economies of scale (SCE) suggest that production expansion can be achieved at a lower cost (with economies or savings). Thus, economies of scale measure the sensitivity of costs with respect to output (Stier, 1985). If the SCE value is positive, production is cheaper as the scale of production rises, suggesting increasing economies of scale. Negative and zero SCE imply diseconomies of scale and constant economies of scale, respectively. Increasing output causes costs to rise or remain constant, providing little incentive for expanding operations.

4.2 Elasticities

Elasticities are additional tools of production analysis that can be recovered from the dual cost function. Several types of elasticities can be calculated using the estimation parameters, including elasticities of substitution and factor demand elasticities.

Allen and Morishima elasticities of substitution between input pairs describe the extent to which inputs are technically substitutable for each other. The measures are similar; Allen substitution elasticity between two inputs is required to be symmetric while Morishima substitution elasticity is not. When elasticities of substitution are positive, production inputs are substitutes; when elasticities are negative, inputs are complements. Magnitude is also important. Values greater than one indicate an elastic relationship between the two inputs; producers can easily substitute between inputs. Values less than one suggest an inelastic response where substitution is difficult. Using ε to denote elasticity,

- if $\varepsilon > 1$, demand is elastic (sensitive to price changes)
- if $\varepsilon = 1$, demand is unit elastic and
- if $\varepsilon < 1$, demand is inelastic (not sensitive to price changes).

Factor demand elasticity quantifies the change in input demand due to a change in input price. When $i = j$, this is own-price elasticity of factor demand; when $i \neq j$, this is cross-price elasticity of factor demand. To agree with economic theory, the sign of any own-price elasticity must be negative; firm demand for any input must decline if the price of that input rises. The sign of cross-price elasticities may be either negative (denoting substitutes) or positive (denoting complements). The magnitude of price elasticity is also important; demand can be elastic, unit elastic, and inelastic with respect to relative price changes.

4.3 Technological Change

Technological change in the production process makes it possible to decrease the amount of inputs needed to produce a given level of output. Technical change is said to be biased toward a particular production input (factor using) if it stimulates the relative use of that input and biased against an input (factor saving) if it reduces use relative to other inputs. In this way, technical progress helps mitigate increasing prices associated with resource scarcity (Lundmark, 2005).

Technical change is called Hicks-neutral if the slopes of the production isoquants are independent of the state of technology. When time is used as a proxy for technology, technical change is Hicks-neutral if at points along the ray from the origin, the marginal rate of substitution is independent from time. In this case, technological change is input-neutral and has no impact on the optimal mix of production inputs.

Initial assumptions about production structure provide the basis for construction and testing of models that approximate behavior observed in the real world (Chambers 1988). Statistical tests were applied before imposing any *a priori* curvature, homogeneity, symmetry, returns to scale, elasticity, or technological change assumptions. Because sawmills generate lumber in response to orders from purchasers who are exogenous entities, the argument that decisions about output levels are exogenous to the firm motivated the use of the cost function approach (Pope, 1982).

5. Estimation Procedure and Models

For estimation purposes, a functional form must be specified for the cost function. The Cobb-Douglas (Cobb and Douglas, 1928) and the transcendental logarithmic (translog) (Berndt and Christensen, 1973) functional forms were selected. These functional forms were selected for ease of implementation, finding comparable results in other studies, testing assumptions about properties of the cost function, comparing the robustness of results to the choice of functional form, and the fact that the translog can test Cobb-Douglas restrictions. The following section describes the procedure for estimating the western Washington lumber industry using a Cobb-Douglas cost function and a translog cost function.

Analysis began by developing a lumber production model using markets for output (lumber) and three input factors (capital labor, and logs). Lumber output was specified as an aggregation of all species and all grades of lumber and considered exogenous at the mill level, which allows the application of the dual cost function in model estimation. Lumber producers faced competitive markets where they had no control over price of output. Input factor prices were also assumed to be established by the market and exogenous to the firm.

The econometric implementation of the model began by specifying the functional relationship:

$$Y = f(K, L, S, T)$$

where

Y = lumber output,
K = capital,
L = labor,
S = logs,
T = the state of technology.

The theory of duality between cost and production functions implies that, given profit maximizing behavior, characteristics of the lumber production function above can be uniquely represented by a dual cost function:

$$C = f(Y, P_K, P_L, P_S, T)$$

where

C = total cost,
Y = lumber output,
P_K = capital price,
P_L = labor price,
P_S= log price, and
T = the state of technology, represented by time in years.

The remainder of this section describes estimation of the Cobb-Douglas and the translog functional forms to investigate the production structure of the western Washington lumber industry.

5.1 The Cobb-Douglas Cost Function

The Cobb-Douglas function is a pioneering production function developed to represent the relationship between inputs and output. For lumber output Y and inputs capital K, labor L, logs S, technology T, and positive constants β_K, β_L, and β_S, the general form of the Cobb-Douglas production function is:

$$Y = f(K^{\beta_K} L^{\beta_L} S^{\beta_S}, T).$$

The Cobb-Douglas production function is inherently homothetic, meaning it is restricted to Hicks-neutral technical change. In this case, estimating a technical change parameter was invalid, the technology variable T was dropped and the dual Cobb-Douglas cost function was:

$$C = f(Y^{\alpha} P_K^{\beta_K} P_L^{\beta_L} P_S^{\beta_S}).$$

C is total lumber production cost, Y is lumber output, P_K, P_L, and P_S are the prices of capital, labor, and logs, respectively.

Log-linearization transforms the function, allowing estimation using least-squares regression. Taking logs (base e) on both sides of the function yields the following linear equation where α and β_i coefficients are parameters for estimation:

$$\ln C = \alpha \ln Y + \beta_K \ln P_K + \beta_L \ln P_L + \beta_S \ln P_S.$$

Applying Shephard's lemma, input coefficients equate to cost minimizing factor demand equations:

$$K = \frac{\partial \ln C}{\partial \ln P_K} = \beta_K$$

$$L = \frac{\partial \ln C}{\partial \ln P_L} = \beta_L$$

$$S = \frac{\partial \ln C}{\partial \ln P_S} = \beta_S$$

Cobb-Douglas cost functions were often estimated after imposing restrictions on the parameters to ensure (rather than test) agreement with principle economic theory. For example, the term $(1 - \beta_L - \beta_S)$ was commonly substituted for β_K to force factor coefficients to satisfy the linear homogeneity assumption described earlier. The test for linear homogeneity is identical to a test for constant economies of scale. If $\beta_L + \beta_S + \beta_K = 1$, the function displays both linear homogeneity and constant scale economies. Similarly, $\beta_L + \beta_S + \beta_K < 1$ implies decreasing and $\beta_L + \beta_S + \beta_K > 1$ implies increasing economies of scale. A Wald coefficient test was applied to determine if constant economies of scale assumptions held for western Washington lumber producers.

Unit changes in logarithms are equivalent to percentage changes; the estimated coefficients β_K, β_L, and β_S are thus input price elasticities measuring the sensitivity of total costs to a change in input K, L, and S prices. With the homogeneity constraint imposed, own- and cross-price elasticities were calculated as (Chambers 1988):

$$\begin{pmatrix} \varepsilon_{LL} & \varepsilon_{LK} & \varepsilon_{LS} \\ \varepsilon_{KL} & \varepsilon_{KK} & \varepsilon_{KS} \\ \varepsilon_{SL} & \varepsilon_{SK} & \varepsilon_{SS} \end{pmatrix} = \begin{pmatrix} \beta_L - 1 & \beta_K & \beta_S \\ \beta_L & \beta_K - 1 & \beta_S \\ \beta_L & \beta_K & \beta_S - 1 \end{pmatrix}.$$

The Cobb-Douglas function represents a first order approximation to an arbitrary cost function (Pope, 1982). The lack of second-order terms restricts the elasticity of substitution between inputs to a constant value of one, a major criticism of the model.

Estimating the Cobb-Douglas cost function--The Cobb-Douglas cost model was estimated with panel data estimation techniques, which combined a time-series component (years) with a cross-sectional component (counties). Panel data analysis created several econometric difficulties; the error term consisted of time-series error, cross-sectional error, and a combination of both (Pindyck and Rubinfeld, 1981).

There was evidence of autoregressive time series error; residuals were serially correlated with their own lagged values. Correction for serial correlation was attempted in two ways; adding a dummy variable for fixed period effects and inserting a first-order autoregressive term (AR(1)) into the regression equation.

Omitted-variable bias and heteroskedasticity were detected in the cross-sectional data component. The omitted variable can be thought of as an individual specific component that cannot be controlled for because it is not observed (Ashenfelter, Levine, and Zimmerman, 2003). In the lumber manufacturing data set, the omitted variable was inherent differences between the counties. These individual differences represented unique fixed attributes, not random variation. The model corrected for omitted variable bias by incorporating a cross-section fixed effects specification allowing for different mixes of underlying production processes across counties. The fixed effect acted like a dummy variable, shifting the intercept up or down for each county.

Heteroskedasticity arose from differences in variance structures across cross-sectional entities that largely stemmed from aggregating mill level data to the county level. Sawmills responding to the mill survey represented a variety of sizes and production technologies; differences in production strategies persisted when mill level data were aggregated to the county level. Correction for heteroskedasticity depends upon assumptions about the underlying variance/covariance structure of the error term. The selected correction allowed for conditional correlation between contemporaneous residuals for cross-sections but restricted residuals in different periods to be uncorrelated. This correction was employed *a priori* as the most plausible match for the data and the specification was estimated using Panel General Least Squares.

There were three ways to analyze panel data: a) assume all model coefficients were identical over time and across counties (constant intercept and slope) so that ordinary least squares estimation was appropriate; b) apply a fixed effects model (also known as a dummy variable model) and assume error terms were fixed parameters that are part of the intercept; or c) use a random effects model that assumes error terms are random variables (Stevens 1991). Based upon the estimation errors described above, the Cobb-Douglas cost function with an added error term and subscripts for time *t* and cross-section county *n* took form (b).

The estimation proceeded as follows: the Cobb-Douglas cost function was first estimated with cross-section and period fixed effects specified:

$$\ln C_{nt} = \psi_n + \varphi_t + \alpha \ln Y_{nt} + \beta_K \ln P_{Knt} + \beta_L \ln P_{Lnt} + \beta_S \ln P_{Snt} + e_{nt}$$

where the intercept term $\psi_n + \varphi_t$ contained a county-specific component ψ_n and a time-specific component φ_t. The Cobb-Douglas was estimated again, but with cross-section fixed effects and an AR(1) correction applied:

$$\ln C_{nt} = \alpha \ln Y_{nt} + \beta_K \ln P_{Knt} + \beta_L \ln P_{Lnt} + \beta_S \ln P_{Snt} + \mathrm{AR}(1) + e_{nt}\,.$$

The two models were then compared; the one with the best fit was used for subsequent calculations. The best fit was determined using the Durbin-Watson statistic for serial correlation and the Jarque-Bera test for normally distributed residuals.

The Cobb–Douglas specification is restricted by unitary elasticity of substitution between input combinations and Hicks-neutral technology. Criticism that this functional form placed severe limitations on model estimation led to the development of flexible functional forms utilizing a simultaneous equation structure. Although virtually supplanted by more flexible function form models like the translog, the Cobb-Douglas form provided a benchmark to compare results obtained from the translog functional form.

5.2 The Translog Cost Function

The translog belongs to the class of flexible functional forms and allows for estimation of elasticity of substitution between factor inputs. The translog relaxes the Cobb-Douglas assumption of unitary elasticity of substitution and allows a nonlinear expansion path to test for non-homotheticity.

The translog production function contains both linear and quadratic terms, providing a second-order approximation to an arbitrary twice differentiable production function with an arbitrary number of inputs (Berndt and Christensen 1973). The three-input translog production function for the western Washington lumber industry is expressed as:

$$
\begin{aligned}
\ln Y \;=\; & \ln\alpha_0 + \alpha_K \ln K + \alpha_L \ln L + \alpha_S \ln S + \alpha_t T \\
& + \frac{1}{2}[\beta_{KL} \ln K \ln L + \beta_{KS} \ln K \ln S + \beta_{KK} (\ln K)^2 \\
& + \beta_{LL} (\ln L)^2 + \beta_{LS} \ln L \ln S + \beta_{LK} \ln L \ln K \\
& + \beta_{SL} \ln S \ln L + \beta_{SS} (\ln S)^2 + \beta_{SK} \ln S \ln K \\
& + \beta_{Kt} \ln KT + \beta_{Lt} \ln LT + \beta_{St} \ln ST + \alpha_{tt} (T)^2]
\end{aligned}
$$

where

Y = lumber output,
K = capital,
L = labor,
S = logs,
T = time, and
α_i and β_{ij} = estimated parameters of the production function.

Logarithmic differentiation with respect to input prices yields the cost share relations:

$$
\begin{aligned}
M_K &= \alpha_K + \beta_{KL} \ln L + \beta_{KS} \ln S + \beta_{KK} \ln K + \beta_{Kt} T \\
M_L &= \alpha_L + \beta_{LL} \ln L + \beta_{LS} \ln S + \beta_{LK} \ln K + \beta_{Lt} T \\
M_S &= \alpha_S + \beta_{SL} \ln L + \beta_{SS} \ln S + \beta_{SK} \ln K + \beta_{St} T
\end{aligned}
$$

where M_K, M_L, and M_S are the proportion of total cost represented by each input. Because they are the first derivatives of the production function, the cost share equations are equivalent to input demand functions. Parameter estimates are generated from simultaneous estimation of the translog production function along with the cost share equations.

The translog cost function is the corresponding dual cost function where arguments are in prices, rather than quantities. The translog cost function representing western Washington lumber production is:

$$\ln C = \ln \alpha_0 + \alpha_Y \ln Y + \alpha_K \ln(P_K) + \alpha_L \ln(P_L) + \alpha_S \ln(P_S)$$
$$+\frac{1}{2}\beta_{KL} \ln(P_K)\ln(P_L) + \frac{1}{2}\beta_{KS} \ln(P_K)\ln(P_S) + \frac{1}{2}\beta_{KK} \ln(P_K)\ln(P_K)$$
$$+\frac{1}{2}\beta_{LL} \ln(P_L)\ln(P_L) + \frac{1}{2}\beta_{LS} \ln(P_L)\ln(P_S) + \frac{1}{2}\beta_{LK} \ln(P_L)\ln(P_k)$$
$$+\frac{1}{2}\beta_{SL} \ln(P_S)\ln(P_L) + \frac{1}{2}\beta_{SS} \ln(P_S)\ln(P_S) + \frac{1}{2}\beta_{SK} \ln(P_S)\ln(P_K)$$
$$+\beta_{KY} \ln(P_K)\ln(Y) + \beta_{LY} \ln(P_L)\ln(Y) + \beta_{SY} \ln(P_S)\ln(Y) + \frac{1}{2}\beta_{YY} \ln(Y)^2$$
$$+\alpha_t T + \frac{1}{2}\alpha_{tt}(T)^2 + \beta_{Kt} \ln(P_K)T + \beta_{Lt} \ln(P_L)T + \beta_{St} \ln(P_S)T + \beta_{Yt} \ln(Y)T$$

where

C = cost,
Y = lumber output,
P_K = capital price,
P_L = labor price,
P_S = log price,
T = time trend representing the state of technology, and
α_i and β_{ij} = coefficients representing the parameters of the cost function.

The first derivatives of the logarithmic translog cost function with respect to inputs capital, labor, and logs again yield the cost share equations M_i, which are equivalent to input demand functions:

$$M_K = \alpha_K + \beta_{KL} \ln(P_L) + \beta_{KS} \ln(P_S) + \beta_{KK} \ln(P_K) + \beta_{KY} \ln(Y) + \beta_{Kt} T$$
$$M_L = \alpha_L + \beta_{LL} \ln(P_L) + \beta_{LS} \ln(P_S) + \beta_{LK} \ln(P_K) + \beta_{LY} \ln(Y) + \beta_{Lt} T$$
$$M_S = \alpha_S + \beta_{SL} \ln(P_L) + \beta_{SS} \ln(P_S) + \beta_{SK} \ln(P_K) + \beta_{SY} \ln(Y) + \beta_{St} T$$

Most of the parameters of lumber production technology can be derived by estimating the share equations alone. However, several parameters appear only in the parent cost function. The optimal procedure is to estimate the translog cost function and the share equations simultaneously as a multivariate system, resulting in a complete set of model parameters (Stier 1985). Banskota, Phillips, and Williamson (1985) described these parameters as “generally meaningless on their own but fundamental to the derivation of important economic relationships”. These coefficients were not so much important in their own right but for the subsequent calculations derived from them.

Estimating the translog cost function--The approach using the translog cost function to analyze lumber production in western Washington most closely resembled the Kant and Nautiyal (1997) model of the Canadian logging industry. First, a cost function with symmetry and linear homogeneity restrictions imposed *a priori* was estimated. These restrictions are required to ensure the model met the minimum requirements for a well-behaved cost function. Symmetry of cross-partial coefficients was imposed using the restriction $\beta_{ij} = \beta_{ji}$. Linear homogeneity with respect to input prices corresponded to the restrictions:

$$\beta_L + \beta_S + \beta_K = 1$$

$$\beta_{LL} + \beta_{LS} + \beta_{LK} = 0$$
$$\beta_{SL} + \beta_{SS} + \beta_{SK} = 0$$
$$\beta_{KL} + \beta_{KS} + \beta_{KK} = 0$$

$$\beta_{LL} + \beta_{SL} + \beta_{KL} = 0$$
$$\beta_{LS} + \beta_{SS} + \beta_{KS} = 0$$
$$\beta_{LK} + \beta_{SK} + \beta_{KK} = 0$$

$$\beta_{LY} + \beta_{SY} + \beta_{KY} = 0$$
$$\beta_{Lt} + \beta_{St} + \beta_{Kt} = 0$$

Linear homogeneity was imposed by dividing all input prices by the price of one arbitrarily chosen input. The cost share equation of the same input was then dropped to avoid covariance matrix singularity. Serial correlation was detected in initial estimates; a first-order autoregressive correction (φ) was added to the model. After imposing symmetry, dividing by P_K, dropping the capital cost share equation, and correcting for serial correlation, the baseline simultaneous equation model for estimation was:

$$\ln\left(\frac{C}{P_K}\right) = \ln\alpha_0 + \alpha_Y \ln(Y) + \alpha_L \ln\left(\frac{P_L}{P_K}\right) + \alpha_S \ln\left(\frac{P_S}{P_K}\right)$$
$$+\frac{1}{2}\beta_{LL} \ln\left(\frac{P_L}{P_K}\right)^2 + \beta_{LS} \ln\left(\frac{P_L}{P_K}\right)\ln\left(\frac{P_S}{P_K}\right) + \frac{1}{2}\beta_{SS} \ln\left(\frac{P_S}{P_K}\right)^2$$
$$+\beta_{LY} \ln\left(\frac{P_L}{P_K}\right)\ln(Y) + \beta_{SY} \ln\left(\frac{P_S}{P_K}\right)\ln(Y) + \frac{1}{2}\alpha_{YY} \ln(Y)^2$$
$$+\alpha_t T + \frac{1}{2}\alpha_{tt}(T)^2 + \beta_{Lt} \ln\left(\frac{P_L}{P_K}\right)T + \beta_{St} \ln\left(\frac{P_S}{P_K}\right)T + \beta_{Yt} \ln(Y)T + \varphi$$

$$M_L = \alpha_L + \beta_{LL} \ln\left(\frac{P_L}{P_K}\right) + \beta_{LS} \ln\left(\frac{P_S}{P_K}\right) + \beta_{LY} \ln(Y) + \beta_{Lt}T + \varphi$$
$$M_S = \alpha_K + \beta_{LS} \ln\left(\frac{P_L}{P_K}\right) + \beta_{SS} \ln\left(\frac{P_S}{P_K}\right) + \beta_{SY} \ln(Y) + \beta_{St}T + \varphi$$

This model served as a benchmark for comparing five more restrictive models to determine the most appropriate specification for the western Washington lumber industry. Parameters of the translog cost function and the labor and log share equations were estimated simultaneously as a system of equations using seemingly unrelated regression (SUR) estimation.

Similar to Nautiyal and Singh (1985), Kant and Nautiyal (1997), and McQueen and Potter-Witter (2006), the benchmark translog cost model was sequentially compared against models of Hicks-neutral technology, no technical change, a homothetic cost function, a homogeneous cost function, and the Cobb-

Douglas specification of unitary elasticity of substitution. The model that best fit the data was subsequently used to calculate economies of scale, elasticities, and technological change.

Restrictions were imposed as follows (Kant and Nautiyal, 1997):

- Hicks-neutral technical change: $\beta_{it} = 0$
- No technical change: $\alpha_t = \alpha_{tt} = \beta_{it} = \beta_{Yt} = 0$
- Homothetic cost function: $\beta_{iY} = 0$
- Homogeneous cost function: $\beta_{iY} = \alpha_{YY} = 0$
- Unitary elasticity of substitution: $\beta_{ij} = 0$.

Likelihood ratio tests (LRT) were used to select between models. The LRT was used to compare goodness-of-fit between the benchmark and a more restrictive model to determine which best fit the data. Using SUR estimation, the LRT was implemented in a two-step process. First, the likelihood ratio (γ) for each restriction was calculated: from the respective determinant residual covariance:

$$\gamma = \frac{\Omega \mathrm{R}}{\Omega \mathrm{U}}^{-\frac{n}{2}},$$

where ΩR and ΩU were determinant residual covariance from the restricted and unrestricted models, respectively and *n* was sample size. The likelihood ratios were then used to compute likelihood test statistics (λ). The likelihood test statistic provided the criterion to determine if restrictions significantly improved the fit between the model and the data:

$$\lambda = -2 * \ln(\gamma) .$$

Likelihood test statistics were compared against chi-square critical values; degrees of freedom corresponded to the number of model restrictions, which varied from two to five (Greene, 2003). The best fitting model was used in subsequent analyses of economies of scale, input substitutability and price elasticity, and technological change.

Scale-- Scale economies (SCE) were derived from the selected translog cost model by first calculating the elasticity of total cost with respect to output Y, also called the elasticity of size (ES):

$$ES = \frac{\partial C}{\partial Y}\frac{Y}{C} .$$

Christensen and Greene (1976) demonstrated an approach for determining economies of scale using the relation:

$$\mathrm{SCE} = 1 - ES.$$

Thus, economies of scale were defined as one minus the elasticity of size. For the translog cost function, the following equation was used to estimate scale economies (Banskota, et al, 1985):

$$\mathrm{SCE} = 1 - (\beta_Y + \beta_{YY} \ln Y + \beta_{KY} \ln P_K + \beta_{LY} \ln P_L + \beta_{SY} \ln P_S + \beta_{Yt} T) .$$

The second term was calculated using parameters from the translog cost model, output quantity and input price values. In all, 256 different scale economy values were calculated, corresponding to the number of observations in the data set. These values were then averaged to generate economies of scale for the western Washington region, biennially, and for each county.

Elasticities--Substitution elasticity measures for production inputs were developed by Allen (1938). Uzuwa (1962) showed that the Allen partial elasticity of substitution can be derived directly from the translog cost function using the expression:

$$\sigma^A{}_{ij} = C \frac{\left(\frac{\partial^2 C}{\partial P_i P_j}\right)}{\left(\frac{\partial C}{\partial P_i}\right)\left(\frac{\partial C}{\partial P_j}\right)}$$

This measure is symmetric, meaning that $\sigma^A{}_{ij} = \sigma^A{}_{ji}$.

Own- and cross-price demand elasticities were derived using input cost shares and the Allen substitution elasticities:

$$\eta_{ii} = M_i \sigma_{ii}{}^A$$
$$\eta_{ij} = M_j \sigma_{ij}{}^A$$
$$\eta_{ji} = M_i \sigma_{ij}{}^A.$$

Morishima substitution elasticities are similar to Allen substitution elasticities, but are not symmetric. Morishima elasticities are calculated from the factor demand elasticities:

$$\sigma^M{}_{ij} = \eta_{ji} - \eta_{ii}$$
$$\sigma^M{}_{ji} = \eta_{ij} - \eta_{jj}.$$

Allen and Morishima elasticities of substitution between factor pairs and own- and cross-price elasticities were calculated from parameters of the translog cost model and input cost shares. Where M_i was the cost share of input i, Allen partial elasticities of substitution between inputs capital, labor, and logs were:

$$\sigma_{KL}{}^A = \left(\frac{\beta_{KL}}{M_K M_L}\right) + 1$$

$$\sigma_{LS}{}^A = \left(\frac{\beta_{LS}}{M_L M_S}\right) + 1$$

$$\sigma_{SK}{}^A = \left(\frac{\beta_{SK}}{M_S M_K}\right) + 1$$

$$\sigma_{KK}{}^A = \frac{\beta_{KK} + M_K{}^2 - M_K}{M_K{}^2}$$

$$\sigma_{LL}{}^A = \frac{\beta_{LL} + M_L{}^2 - M_L}{M_L{}^2}$$

$$\sigma_{SS}{}^A = \frac{\beta_{SS} + M_S{}^2 - M_S}{M_S{}^2}$$

Own- and cross-price elasticities of factor demand were proportional to Allen substitution elasticities. Own-price elasticities for labor, logs, and capital were calculated as:

$$\eta_{LL} = M_L \sigma_{LL}{}^A$$
$$\eta_{SS} = M_S \sigma_{SS}{}^A$$
$$\eta_{KK} = M_K \sigma_{KK}{}^A$$

and cross price elasticities as:

$$\eta_{LK} = M_K \sigma_{LK}{}^A$$
$$\eta_{KL} = M_L \sigma_{LK}{}^A$$
$$\eta_{LS} = M_S \sigma_{LS}{}^A$$
$$\eta_{SL} = M_L \sigma_{LS}{}^A$$
$$\eta_{SK} = M_K \sigma_{SK}{}^A$$
$$\eta_{KS} = M_S \sigma_{SK}{}^A.$$

Morishima elasticities of substitution were derived from own- and cross-price elasticities:

$$\sigma_{LK}{}^M = \eta_{KL} - \eta_{LL}$$
$$\sigma_{KL}{}^M = \eta_{LK} - \eta_{KK}$$
$$\sigma_{LS}{}^M = \eta_{SL} - \eta_{LL}$$
$$\sigma_{SL}{}^M = \eta_{LS} - \eta_{SS}$$
$$\sigma_{KS}{}^M = \eta_{SK} - \eta_{KK}$$
$$\sigma_{SK}{}^M = \eta_{KS} - \eta_{SS}.$$

Elasticities were also calculated at three different scales. Substitution, own- and cross-price elasticities were generated for the entire westside region, biennially, and for each county. For the region, elasticities were evaluated after fixing cost shares at their mean values. Biennial elasticities were evaluated at the mean of cost shares for each period. County-level elasticities were calculated as the mean elasticity values per county after allowing cost shares to vary.

Technical change-- The rate and bias of technological change in the western Washington lumber industry was examined using properties of the translog cost function. The rate of technical change (TC) measures productivity growth unrelated to input variables. TC is defined as:

$$\mathrm{TC} = -\left(\frac{\partial \ln C}{\partial T}\right)\left(\frac{\partial \ln C}{\partial \ln Y}\right)^{-1}.$$

The first term is the rate of change in costs with respect to time, called the rate of cost diminution (Chambers 1988). The second term is the elasticity of cost with respect to output (Stier 1980, Baardsen 2000).

The rate of technological change (TC) was estimated for the westside region, over time, and by county as:

$$-TC = \left(\alpha_t + \alpha_{tt}T + \beta_{Lt}\ln P_L + \beta_{St}\ln P_S + \beta_{Kt}\ln P_K + \beta_{Yt}\ln Y\right)/\left(ES\right)$$

where the first term is the derivative of the translog cost function with respect to time measured with a linear time trend *T*, called the rate of cost diminution (Chambers 1988). The second term *(ES)* is the elasticity of size discussed earlier. When technical change is biased, the rate of bias for the *i*th input is defined as:

$$b_i = \left(\frac{\partial M_i}{\partial T}\right)\left(\frac{1}{M_i}\right) = \frac{\beta_{it}}{M_i},$$

where M_i is the factor share of input X_i, calculated at the mean of input cost shares. When b_i is less than, equal to, or greater than zero, technical change is interpreted as input saving, neutral, or using, respectively (Chambers, 1988).

6. Data

The empirical analysis is based on the behavior of sawmills in western Washington from 1972 to 2002. Data series were compiled from several sources and organized as a balanced panel after pooling cross-section and time series data. Ideally, the unit of observation is the sawmill. Since mill level data are available for only some series, the unit of observation was ultimately aggregated to the county level. Although there are 19 counties in western Washington, three (Island, San Juan, and Wahkiakum Counties) were omitted owing to irresolvable data inconsistencies. The resulting data set contains a time series of 16 years arranged biennially from 1972 to 2002 and a cross-sectional series containing 16 westside Washington counties, a panel of 256 observations.

Data for sawmill and timber characteristics were primarily taken from the Washington Department of Natural Resources' biennial mill survey (WADNR 1972-2002a). The sawmill questionnaire covers mill characteristics, total operating hours, log consumption, and lumber production. Because the survey contains no information on capital, prices, and costs, these data were acquired from other published sources. Since mill identities were confidential, labor and capital costs and output and factor prices could not be linked to specific facilities. Data sources are discussed in detail next.

6.1 Employment

County level employment information by industrial classification code was published annually for all states in the U.S. Census Bureau's County Business Patterns (U.S. Department of Commerce, Bureau of the Census, 1972-2002b). From 1972 to 1996, data for lumber manufacturing were listed under Standard Industrial Classification (SIC) code 242. After 1996, the Census Bureau converted from the SIC system to the North American Industrial Classification System (NAICS), adopted nationally in 1997 (U.S. Department of Commerce, 2006). The NAICS code 3211 most closely matches SIC 242 and was used for the period from 1998 to 2002. The main differences were that the 3211 NAICS code includes wood preservation establishments and does not contain mills that resaw lumber or manufacture hardwood dimension lumber and flooring.

Annual payroll values, when available, represented total labor cost and were used as the labor cost share. Sadly, total payroll was not consistently available for every county owing to disclosure laws designed to protect confidentiality of reporting firms. Missing payroll values were generated in two ways. If the year immediately prior and immediately following the missing value were reported, the missing value was calculated as the average of those two values. If several consecutive years were missing, values were generated using reported data for SIC 24 and NAICS 321 and the number of firms (listed in County Business Patterns) according to the ratio (for SIC): $\frac{\text{SIC 24 payroll}}{\text{\#SIC 24 firms}} = \frac{\text{SIC 242 payroll}}{\text{\#SIC 242 firms}}$. All values were adjusted to real 1982 dollars using the all-commodity producer price index (PPI).

Labor price was calculated as dollars per hour worked by production workers. Total hours of mill operation were published in the WADNR mill surveys (1972-2002a). Data were aggregated to the county level and wages were calculated by dividing total payroll expense (in real terms) by number of hours worked. The two final labor series contained labor total cost and real wages for 16 westside counties spanning the even-numbered years from 1972 to 2002.

6.2 Logs

The log cost series was calculated by multiplying the quantity of logs consumed in each county by a log price. The WADNR Mill Survey (1972-2002a) published the total volume (MBF) of logs consumed by sawmills in the sixteen western Washington counties. Log quantity was measured in thousand board feet, Scribner log rule.

All log prices were adjusted to 1982 dollars using the all-commodity PPI. Three sources were used to construct the log price series. Log prices from 1972 to 1985 were compiled by the Industrial Forestry Association and published annually in the second quarter by the USDA Forest Service (Warren, various years). Log price by species and grade were reported for the Pacific Northwest region, encompassing western Washington and northwestern Oregon. The 1972-85 log price series was generated by averaging the price for number 1, number 2, number 3, and number 4 domestic grades of Douglas-fir and western hemlock. Because of the regional price reporting, all counties had the same log price for this time period. This price series was discontinued in 1985.

Log prices for the years from 1982 to 1989 came from the Forest Price Report published by the National Agricultural Statistics Service (NASS). The Forest Price Report was published six times a year, in January, March, May, July, September, and November. Western Washington was divided geographically into three sub-regions. For each sub-region, a log price series was constructed by averaging Douglas-fir and hemlock-fir prices over four domestic grades: special mill, number 2, number 3, and number 4. Each county was assigned one of three possible log prices for the year 1988, depending on location. This data set was discontinued in 1989, but copies are available through the NASS website.

After 1988, delivered log prices for western Washington were reported at three sub-regional levels in Log Lines (Log Lines Reporting Service, 1989-2002). Monthly prices for Douglas-fir and western hemlock special mill, number 2, number 3, and number 4 grades were averaged for each sub-region. All counties in any region were assigned the same price, with two exceptions. Jefferson County log prices were averaged values for region 1 and region 2; Pacific County prices were averaged values for region 2 and region 3. Thus, there were five possible log prices assigned to the 16 counties.

6.3 Capital

The total cost of capital series was constructed based on methodology used by Stevens (1991). Stevens created a capital stock series by measuring changes in the assessed value of machinery and equipment used in sawmills, collected from each County Assessor's office. The subsequent capital stock series was developed based on the perpetual inventory method by Christensen and Jorgenson (1969):

$$\Delta K_t = \frac{(I_t - D_t K_{t-1})}{P_t} \ ,$$

where ΔK_t = changes in real capital stock from period t-1 to period t,
I_t = investment in the current period,
K_{t-1} = capital stock in the previous period,
D_t = depreciation and
P_t = producer price index.

This formula was modified in two ways. Because county appraisers consider depreciation when evaluating properties, depreciation was assumed to be incorporated into assessed values. Therefore, the term D_t was omitted. The resulting series was also adjusted for the service life of capital stock, which, as discussed below, was measured using building values, rather than machinery and equipment like Stevens (1991). Baardsen (2000) adjusted building values by a rate of replacement where the lifespan for buildings was estimated as 25 years. The final capital stock series was calculated as:

$$\Delta K_t = \frac{(K_t - K_{t-1} + (1 - 1/25)K_{t-1})}{P_t} \ ,$$

where ΔK_t = changes in real capital stock from period t-1 to period t,

K_t = current period assessor value,
K_{t-1} = previous period assessor value, and
P_t = producer price index.

Initial capital stock values were obtained from visiting the sixteen County Assessor offices and state archive facilities in Olympia, Bellevue, and Bellingham to obtain assessed real property values for sawmills that responded to the WADNR mill survey over the study period. The most consistent assessments across counties were for buildings and land; thus, building values were used for the capital stock series. Although personal property may a better measure, counties either did not store records back to 1972 or refused to divulge personal property information for fear of violating disclosure laws.

Despite an exhaustive search, assessment records for several mills were incomplete, lost, or destroyed. Many counties did not retain assessment records back to 1972 and had not sent historic documents to state archive facilities. Missing sawmill assessment values were estimated by regressing annual capacity on existing assessed values. Annual capacity was calculated by multiplying maximum eight-hour capacity from the WADNR Mill Survey by number of operating days and number of shifts.

Four regression equations were developed for each DNR region (Lower Columbia, Olympic Peninsula, and Puget Sound) based on maximum eight-hour capacity. Regression equations and number of observations by DNR region were:

Lower Columbia

$$\text{Assessed Value}_{LC<40} = 12813.12(\textstyle\sum \text{annual max capacity}_{LC<40}),\ n = 21$$

$$\text{Assessed Value}_{40\leq LC\geq 80} = 17428.05(\textstyle\sum \text{annual max capacity}_{40\leq LC\geq 80}),\ n = 34$$

$$\text{Assessed Value}_{80\leq LC>120} = 143029.60(\textstyle\sum \text{annual max capacity}_{80\leq LC>120}),\ n = 25$$

$$\text{Assessed Value}_{LC\geq 120} = 284164.10(\textstyle\sum \text{annual max capacity}_{LC\geq 120}),\ n = 74$$

Olympic Peninsula:

$$\text{Assessed Value}_{OP<40} = 14568.93(\textstyle\sum \text{annual max capacity}_{OP<40}),\ n = 78$$

$$\text{Assessed Value}_{40\leq OP\geq 80} = 13422.63(\textstyle\sum \text{annual max capacity}_{40\leq OP\geq 80}),\ n = 53$$

$$\text{Assessed Value}_{80\leq OP>120} = 48574.53(\textstyle\sum \text{annual max capacity}_{80\leq OP>120}),\ n = 35$$

$$\text{Assessed Value}_{OP\geq 120} = 43404.15(\textstyle\sum \text{annual max capacity}_{OP\geq 120}),\ n = 145$$

Puget Sound:

$$\text{Assessed Value}_{PS<40} = 1471.81(\textstyle\sum \text{annual max capacity}_{PS<40}),\ n = 97$$

$$\text{Assessed Value}_{40\leq PS\geq 80} = 6107.83(\textstyle\sum \text{annual max capacity}_{40\leq PS\geq 80}),\ n = 66$$

$$\text{Assessed Value}_{80\leq PS\geq 120} = 441.78(\textstyle\sum \text{annual max capacity}_{80\leq PS\geq 120}),\ n = 66$$

$$\text{Assessed Value}_{PS\geq 120} = 13240.00(\textstyle\sum \text{annual max capacity}_{PS\geq 120}),\ n = 183$$

The result was an assessed value (actual or estimated) for each sawmill for every year that mill responded to the WADNR mill survey. Assessed values for the mills located in each county were then summed to generate the capital cost series.

Next, the price of capital services was constructed using the capital stock series, county property tax rates, and a discount rate. Capital stock was multiplied by a discount rate, represented by Moody's AAA Corporate Bond Rate, as a proxy for opportunity cost of investment (Stevens 1991). The Washington State Department of Revenue publishes average property tax levy rates by county and by year (Washington Department of Revenue, various years). Levy rates were multiplied by the assessed value of sawmills to calculate an aggregated tax burden of sawmills for each county. This estimated value of property taxes was added to the opportunity cost of investment to arrive at a capital price that was specific to each county.

6.4 Lumber

The translog cost model only requires output quantity data. Volume of lumber output from Washington sawmills (thousand board feet, lumber tally) was available in the WADNR Mill Survey. The mill survey does not specify grade of lumber output; the data series consists of an all-species and all-grade total of lumber produced by county.

The left-hand side variables of the translog cost function and cost share equations were derived from capital, labor, and log total cost data. Total cost was the sum of capital, labor, and log costs; cost shares were calculated as the proportion of total cost represented by each of the three inputs.

6.5 Data Limitations

Much of the data, such as mill survey and assessed values, are firm level. Lack of labor payroll data at the mill level precluded firm level production analysis and data were aggregated to the county level. One disadvantage of aggregating data is the loss of localized trends in the aggregation process.

Another difficulty is the inconsistent time intervals used in different data series. Mill surveys are published biennially on even-numbered years. Real property values are reassessed inconsistently, from every four years in some counties to every year in others. The remaining data are available annually, quarterly, or monthly. Merging these disparate time series introduces a potential source of error.

Classification between real property and personal property was inconsistent across counties. There was some subjectivity as to what type of property was appraised as real and added into improvement values. These classifications may not be uniform between counties or even within a county at different assessment periods. Steven (1991) reported encountering the same issue.

The reported labor data has three possible problems. First, total payroll and manhours worked originate from different data sources. The number of reporting firms is not the same. Second, employment is often reported in the county containing the company headquarters, even though manufacturing occurs elsewhere. As a result, lumber industry employment may be overrepresented in some counties and underrepresented in others. Third, the U.S. Census Bureau describes the bridge between SIC and NAIC systems as somewhat open. Although wood products manufacturing industries comprising SIC242 and NAICS3211 do not match exactly, the 1997 Economic Census declares sales or receipts from NAICS are within 3 percent of SIC sales or receipts (U.S. Department of Commerce, 2006).

7. Results

This section presents western Washington lumber production analysis results using Cobb-Douglas and translog cost models. Results from two Cobb-Douglas specifications are presented first, including factor demand equations, measures of scale economy, and input demand elasticities. Translog specification results follow, including calculations of scale economies, elasticities, and technical change at three scales: Washington westside region, county, and over time. The Cobb-Douglas and regional translog model are then compared for robustness of results to model selection.

7.1 Cobb-Douglas Cost Function

Two models were developed using the Cobb-Douglas cost function. Both used fixed cross-section effects; the models differed by correction for time series error. This section presents results and compares the two models according to significance of regression coefficients, goodness of fit, success of correction techniques, and agreement with economic theory.

Regression coefficients with standard errors and scale economy tests from the two Cobb-Douglas cost function models are presented in Table 2. With the fixed cross-section and period effects model, all regression coefficients are significant with 99 percent confidence. The intercept value ($\psi_n + \varphi_t$) of 3.313 suggests that underlying production structure differs between counties and/or between time periods. The R-squared value of 0.980 indicates a good fit between data and model. The Durbin-Watson statistic suggests persistence of serial correlation error. Jarque-Bera test statistic was rejected at the 99 percent level; there is no evidence of normally distributed residuals. The Wald coefficient test that $\beta_L + \beta_S + \beta_K =$ 1 was rejected; linear homogeneity and constant economies of scale hypotheses do not hold. In this model, $\beta_L + \beta_S + \beta_K > 1$, indicating lumber producers displayed increasing economies of scale.

Table 2. Regression coefficients from the Cobb-Douglas cost function

Coefficient	Cross-section effects, period effects	Cross-section effects, AR(1) correction
$\psi_n + \varphi_t$	3.3129** (1.0065)	
ψ_n		5.0325** (0.5478)
α	0.5093** (0.0340)	0.4586** (0.0282)
β_L	0.1569** (0.0224)	0.1656** (0.0236)
β_S	0.8420** (0.1511)	0.7288** (0.0564)
β_K	0.1825** (0.0177)	0.1422** (0.0195)
AR(1)		0.5451** (0.0600)
R-squared	0.9802	0.9834
Durbin-Watson	1.1114	2.1187
Jarque-Bera	reject	cannot reject
Linear homogeneity	reject	cannot reject
Economies of scale	$\beta_K + \beta_S + \beta_L = 1.1814$ increasing returns to scale	$\beta_K + \beta_S + \beta_L = 1.0367$ constant returns to scale

** 99% significance

Results from the second model with cross-section fixed effects and a correction for first-order serial correlation also appear in Table 2. All regression coefficients, including the correction term, are significant at the 99 percent confidence level. The AR(1) correction coefficient suggests that about half of the variation in period *n* is explained by the previous period. The intercept value of 5.033 corresponds to cross-section fixed effects and shows a significant difference across counties. Interestingly, the cross-section fixed effect alone is more pronounced than when combined with period effects in the previous model. The R-squared value of 0.983 indicates a slightly better fit than the fixed period effects model. The Durbin-Watson statistic rejects the hypothesis of serial correlation and normally distributed residuals could not be rejected using the Jarque-Bera statistic, two results that conflict with the previous model.

Another conflicting result is that the coefficient test $\beta_K + \beta_L + \beta_S = 1$ was not rejected. Linear homogeneity and constant scale economies assumptions hold, a result that is consistent with economic theory. Agreement between theory and empirical results and general model performance motivated using the AR(1) correction model in subsequent analysis.

At the county level, unobservable heterogeneity contributed significantly to differences in cost structures in most cases (Table 3). Fixed effects represent a shift in the intercept of the Cobb-Douglas regression equation for each county. Counties with relatively high negative values like Skamania, Whatcom, and Thurston Counties had differences resulting in lower total production costs. On the other hand, Snohomish, Cowlitz, and Lewis Counties had greater costs, all else held equal. These values suggest there was considerable variation in lumber manufacturing cost across counties, which was not explained by the model. The source of this variation remains unclear.

Table 3. Fixed effects by county for the Cobb-Douglas cost function

County	Fixed Effects
Skamania	-0.4269
Whatcom	-0.3769
Thurston	-0.3730
Jefferson	-0.3141
Clark	-0.2746
Kitsap	-0.1665
Pacific	-0.1118
Skagit	-0.0752
Clallam	-0.0049
King	0.0122
Mason	0.0820
Pierce	0.3358
Grays Harbor	0.3632
Lewis	0.3807
Cowlitz	0.3833
Snohomish	0.5232

Cobb-Douglas regression coefficients equate to both input demand functions and factor demand elasticities. Coefficients β_K, β_L, and β_S represent a point estimate of fixed-factor demand for capital, labor, and logs for the panel data set. Capital, labor, and logs attributed to 14.22, 16.56, and 72.88 percent of lumber production costs over the study period, respectively. This result suggests mill sensitivity to trends in log markets.

The Cobb-Douglas coefficients also correspond to input and output demand elasticities because of log transformation of the regression equation. Elasticities measure the percentage change in total cost for every one percent change in input price, all else equal. Capital, labor, and log input demand elasticities were 0.1422, 0.1656, and 0.7288, respectively. Each value is less than one, implying that factor demand was inelastic. Production costs were most elastic with respect to changes in log price; every one percent rise in log prices increased total costs by 0.72 percent. Capital and labor elasticities suggest that costs were slightly more sensitive to changes in wage than capital price. Elasticity of costs with respect to lumber output is 0.4586; every one percent increase in lumber production caused a corresponding 0.46 percent increase in production costs.

Own and cross price elasticities--Own- and cross-price elasticities using the Cobb-Douglas cost function appear in Table 4. All own-price elasticities were negative in sign, in agreement with economic theory. Of the three inputs, demand for capital was most elastic with respect to changes in its own price. The capital own-price elasticity value of -0.8578 indicates that a one-percent rise in capital price led to a 0.86 percent decline in capital demand Labor demand was slightly less elastic than capital demand; log demand was the least responsive to changes in own price.

Table 4. Cobb-Douglas own- and cross-price demand elasticities

Input	Price of labor	Price of capital	Price of logs
Labor	-0.8344	0.1422	0.7288
Capital	0.1656	-0.8578	0.7288
Logs	0.1656	0.1422	-0.2712

Cross price elasticities represent the extent that demand for one input responds to price changes in another. Table 4 shows that cross-price elasticities involving logs were the most inelastic. Demand for labor and capital was highly responsive to changes in log price; a one percent increase in log price led to a 0.73 percent decline in labor and log demand. Similarly, changes in labor and capital price led to almost no change in log demand. Capital and labor demand were relatively unaffected by changes in each other's price as well. Own- and cross-price elasticities suggest that log price had the strongest influence on production costs and decisions in western Washington sawmills.

Although the Cobb-Douglas cost function provides some general insight into the production structure in western Washington, this model has limitations. The unitary elasticity of substitution inherent in the Cobb-Douglas prevented testing whether inputs are substitutes or complements in the production process or determining the magnitude of substitution possibilities. Hicks-neutral technology prohibited any estimation of technological change. In the next section, results of lumber production analysis using the translog flexible form cost function are presented. Later, the translog is compared against the Cobb-Douglas to determine whether results were robust to model choice.

7.2 Translog Cost Function

A translog cost model with linear homogeneity and symmetry restrictions established a benchmark for testing five assumptions commonly imposed on production models. Likelihood ratio tests rejected all restrictions with 99 percent confidence (Table 5). Note that the Cobb-Douglas specification of unitary elasticity of substitution was rejected, indicating the Cobb-Douglas cost function was an inappropriate model for lumber production in western Washington. Subsequent calculations of scale effects, elasticities, and technology effects were based on parameters from the benchmark model, which exhibited nonconstant returns to scale, nonunitary elasticity of substitution, and biased technical change.

Table 5. Likelihood ratio test results for translog restrictions

Model	No. of restrictions	Determinant residual covariance	Likelihood ratio	Likelihood ratio test statistic	Chi-square 99% critical value	Outcome
Benchmark	0	8.34E-08				
Hicks neutral technology	2	9.42E-08	2.31E-07	30.565	9.21	Reject
No technical change	5	1.02E-07	1.06E-11	50.532	15.09	Reject
Homothetic	2	2.26E-07	4.63E-55	250.219	9.21	Reject
Homogeneous	3	2.32E-07	1.73E-56	256.795	11.34	Reject
Unitary elasticity of substitution	3	2.63E-07	2.52E-63	288.275	11.34	Reject

Coefficient estimates and standard errors from the translog cost function appear in Table 6. The model was run three times, each with a different cost share equation omitted. Parameter coefficients were invariant to which cost share equation was dropped.

Table 6. Estimates of cost function parameters

Parameter	Coefficient	Std. Error	t-Statistic	Prob.
α_0	11.6783	1.9432	6.0098	0.0000
α_Y	-1.0328	0.3186	-3.2414	0.0012
β_L	0.9009	0.0964	9.3493	0.0000
β_S	-0.6073	0.1054	-5.7618	0.0000
β_K	0.7064	0.0964	7.3317	0.0000
β_{LL}	0.1041	0.0071	14.6337	0.0000
β_{LS}	-0.0973	0.0068	-14.2740	0.0000
β_{LK}	-0.0067	0.0051	-1.3213	0.1868
β_{SS}	0.1578	0.0093	16.9391	0.0000
β_{SK}	-0.0605	0.0060	-10.0839	0.0000
β_{KK}	0.0672	0.0064	10.4408	0.0000
β_{YL}	-0.0694	0.0088	-7.9300	0.0000
β_{YS}	0.1714	0.0091	18.8239	0.0000
β_{YK}	-0.1020	0.0092	-11.1187	0.0000
β_{YY}	0.2115	0.0311	6.7944	0.0000
α_t	-0.1461	0.1224	-1.1938	0.2330
$\alpha\alpha_{tt}$	0.0011	0.0073	0.1531	0.8784
β_{LT}	0.0046	0.0029	1.5685	0.1172
β_{ST}	-0.0180	0.0033	-5.3878	0.0000
β_{KT}	0.0134	0.0027	4.8747	0.0000
β_{YT}	-0.0013	0.0060	-0.2135	0.8310
φ	0.8596	0.0188	45.6653	0.0000

Curvature requirements--Production theory defines a well-behaved cost function as concave in input prices with output demand functions that are strictly positive. These curvature requirements were tested on the lumber data set. The concavity condition was met in all but two cases; the Hessian matrix of second-order partial derivatives was symmetric and negative semi-indefinite. The requirement of strictly positive demand functions was satisfied for each biennial observation as well; cost shares were positive at all points. Therefore, the estimated translog cost function was considered well-behaved, meaning the translog was an appropriate choice of functional form for the western Washington lumber industry.

Factor demand functions--Cost shares represent the proportion of total costs attributed to each production input. Because they arise from the necessary first order conditions for cost minimization, cost shares equate to lumber input demand functions. Descriptive statistics for capital, labor, and log cost shares are listed in Table 7. Logs were responsible for 58 percent of production costs on average, somewhat smaller than the Cobb-Douglas value of 72 percent. Labor followed with 24 percent and capital with 18 percent of costs over the study period. Although labor and capital contributions to costs were smaller than logs on average, maximum values of 71 and 61 percent suggest that averaging labor and capital costs masked impacts at the individual mill level.

Table 7. Descriptive statistics for input factor cost shares

	Cost share		
	Capital	**Labor**	**Logs**
Mean	0.1839	0.2368	0.5793
Median	0.1629	0.2140	0.5906
Maximum	0.6077	0.7125	0.8554
Minimum	0.0144	0.0505	0.1436
Std. Deviat.	0.1277	0.1226	0.1255
Skewness	0.9936	1.4388	-0.5384
Kurtosis	3.5842	5.3355	3.2930
Jarque-Bera	44.8710	143.6493	13.0238
Probability	0.0000	0.0000	0.0015
Observations	256	256	256

Economies of scale--Economies of scale are defined as the relative decrease in costs resulting from an increase in quantity of output produced. Scale economies were calculated at three different scales, regionally, biennially, and by county. Regionally, economies of scale for the westside Washington lumber industry equaled 0.418 when evaluated at the mean. The positive value of 0.418 indicates that sawmills enjoyed a cost advantage with increased scale of production.

Economies of scale (SCE) were also calculated biennially to provide insight into lumber production trends over time. SCE fell in 1978, then rose to a peak near 0.55 in 1982, and then declined for six subsequent biennia to an all-period low in 1994 (Figure 21). While values of scale are positive throughout the last three decades, there appears to be a slightly declining trend.

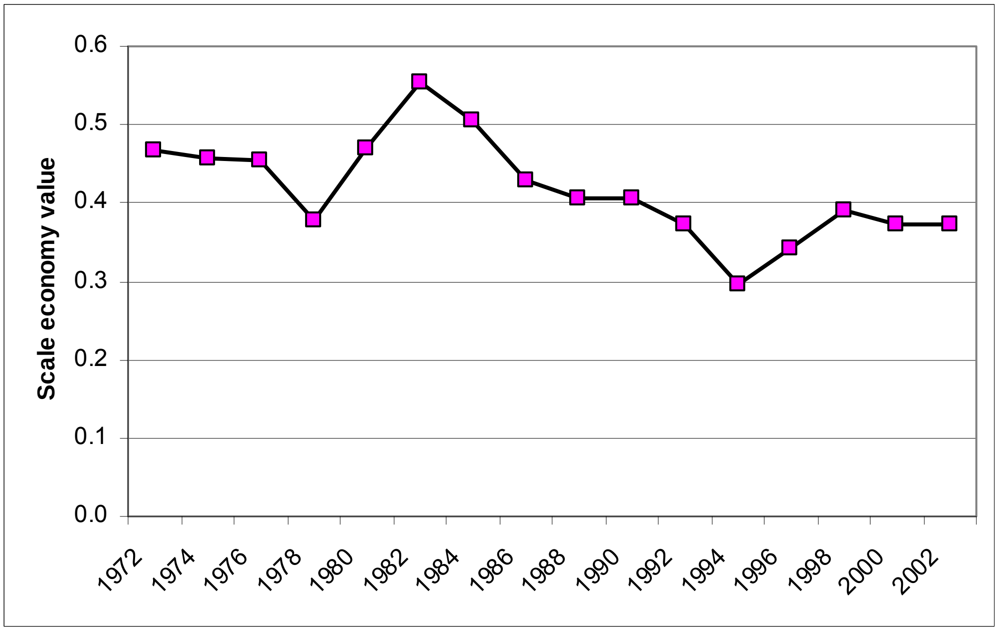

Figure 21. Economies of scale over time

The average scale economy value for each western Washington county is displayed in Table 8. Shading indicates county-level values that exceed the regional average. Counties with the greatest scale economy had the greatest potential to decrease costs by expanding production. At the opposite end were counties with scale economy values lower than average; output expansion led to cost savings that exhausted scale economies. With a value of 0.158, Snohomish County exhibited the lowest economies of scale.

Table 8. Economies of scale by county

County	Scale economy
Jefferson	0.5561
Kitsap	0.5372
Whatcom	0.5293
Clallam	0.5171
Pacific	0.5160
Grays Harbor	0.5096
Clark	0.4960
Thurston	0.4668
Skamania	0.4279
Skagit	0.4034
Cowlitz	0.3367
Mason	0.3307
King	0.3236
Pierce	0.3141
Lewis	0.2843
Snohomish	0.1583

Elasticities--Allen and Morishima partial elasticities of substitution, own- and cross-price elasticities were calculated using the benchmark translog specification. Like scale economies, elasticities were examined at regional, biennial, and county-level scales. Allan elasticities measure the change in input *i* associated with a change in the price of input *j*. Morishima elasticities measure the change in the input ratio *i*, *j* with a change in the price of input *j*.

Allen partial elasticities of substitution--Regionally, Allen elasticities between capital and labor, capital and logs, and labor and logs were positive in sign (Table 9). Inputs were substitutes in lumber production technology with the greatest ease of substitution occurring between capital and labor (0.8455). Log-capital substitution elasticity was an inelastic 0.4322, indicating they were about 2 times less easily substituted than capital and labor. Labor and logs were least substitutable in western Washington sawmills (0.2904).

Table 9. Regional Allen substitution elasticities

	Capital	Labor	Logs
Capital		0.8455	0.4322
Labor			0.2904
Logs			

Table 10 displays Allen substitution elasticities for each input combination over time. Values are less than one in all cases and positive with exception of the 1972 log-labor estimate, indicating that input relationships were inelastic substitutes. Capital-labor substitution elasticities were the least volatile and consistently remained near 0.8 (Figure 22). Log-capital and log-labor substitution became more difficult over time, trending downward in value from near 0.4 in 1984 to near 0.2 in 2002.

Table 10. Allen substitution elasticities by year

Year	Capital-Labor	Log-Capital	Labor-Log
1972	0.7709	0.6006	-0.2291
1974	0.7786	0.5231	0.0357
1976	0.8139	0.5213	0.1113
1978	0.7956	0.4688	0.1704
1980	0.8725	0.5145	0.2134
1982	0.9010	0.4674	0.2834
1984	0.8817	0.3676	0.3689
1986	0.8524	0.4355	0.2947
1988	0.8307	0.3464	0.3485
1990	0.8415	0.3284	0.3705
1992	0.8319	0.3118	0.3725
1994	0.7298	0.2228	0.3213
1996	0.7892	0.2199	0.2652
1998	0.8525	0.2789	0.2788
2000	0.8453	0.3267	0.2386
2002	0.8406	0.1843	0.1679

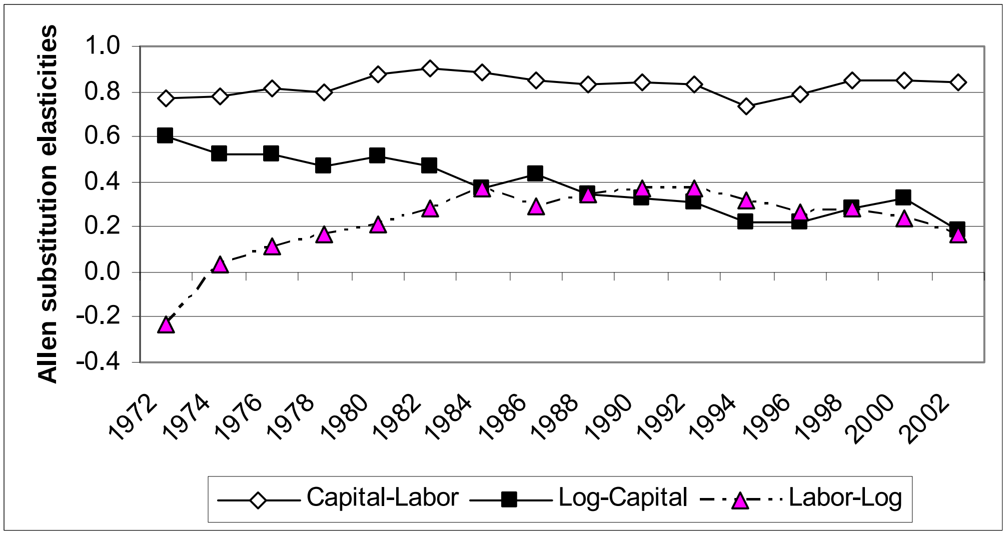

Figure 22. Allen substitution elasticities by year

Allen substitution elasticities at the county level also show that demand for inputs was inelastic with a few exceptions (Table 11). Capital and labor were substitutes in all counties, varying from highs near 0.89 in Grays Harbor County to a low of 0.36 in Snohomish County. Logs and capital were compliments in five of the 16 counties; Clallam, King, Skagit, Snohomish and Whatcom counties had elasticities less than zero. Logs and capital were strongest complements in Whatcom, Skagit, and Snohomish mills; capital use could not increase without greater use of logs and vice versa. Logs and capital were strongest substitutes in Grays Harbor and Pacific Counties, although the relationship was inelastic. These two counties, in addition to Kitsap and Mason counties, demonstrated complimentary use of labor and logs. Substitution between labor and logs was generally low with exception of Whatcom, Skagit, and Snohomish mills, although elasticities for these two counties were fairly inelastic.

Table 11. Allen substitution elasticities by county

County	Capital-Labor	Log-Capital	Labor-Log
Clallam	0.8522	-0.0991	0.2018
Clark	0.7802	0.0566	0.2434
Cowlitz	0.8253	0.5053	0.0807
Grays Harbor	0.8882	0.6443	-0.6662
Jefferson	0.7390	0.4158	0.0384
King	0.5957	-0.1102	0.2499
Kitsap	0.6076	0.4678	-0.5254
Lewis	0.7499	0.2757	0.1887
Mason	0.7847	0.5392	-0.1384
Pacific	0.8323	0.6068	-0.4025
Pierce	0.7352	0.2833	0.2421
Skagit	0.5129	-1.1941	0.4361
Skamania	0.5496	0.0214	0.1323
Snohomish	0.3557	-0.9136	0.4263
Thurston	0.7533	0.1455	0.2349
Whatcom	0.4797	-3.5676	0.4888

Morishima partial elasticities of substitution--Unlike Allen substitution elasticities, Morishima partial elasticities of substitution are not symmetric. All input combinations were positive in sign and inelastic at the regional level (Table 12). Capital and labor remained the strongest substitutes; with an elasticity of 0.61, capital was slightly more easily substituted for labor than the converse (0.52). Capital was also more easily substituted for logs than logs for capital. Labor could be substituted for logs more easily than logs for labor. Consistent with Allen substitution elasticities, capital and labor were the strongest Morishima substitutes and labor and logs the weakest.

Table 12. Regional Morishima substitution elasticities

	Capital	Labor	Logs
Capital		0.6061	0.5301
Labor	0.5239		0.3925
Logs	0.3986	0.3165	

Morishima substitution elasticities calculated biennially provide insight into the timing of changes in the relationship between production inputs (Table 13). Capital-labor elasticities began at 0.13 and stabilized around 0.5 by 1980. Labor-capital elasticities started over 0.6 and remained stable throughout the period. Downward trends in values were observed starting in the late 80s indicating that substitution possibilities declined over time.

Table 13. Morishima substitution elasticities by year

Year	Capital-Labor	Labor-Capital	Capital-Log	Log-Capital	Labor-Log	Log-Labor
1972	0.1319	0.6621	0.4978	0.6217	-0.0324	0.0079
1974	0.2964	0.6128	0.4473	0.5628	0.1309	0.1809
1976	0.3792	0.6329	0.4487	0.5731	0.1950	0.2548
1978	0.3974	0.5875	0.4139	0.5290	0.2238	0.2822
1980	0.5162	0.6790	0.4456	0.5965	0.2828	0.3653
1982	0.6069	0.6945	0.4150	0.5911	0.3273	0.4307
1984	0.6205	0.6199	0.3680	0.5233	0.3687	0.4652
1986	0.5348	0.6150	0.4014	0.5365	0.3212	0.3996
1988	0.5463	0.5451	0.3469	0.4691	0.3481	0.4241
1990	0.5717	0.5476	0.3398	0.4669	0.3638	0.4445
1992	0.5638	0.5284	0.3279	0.4501	0.3633	0.4417
1994	0.4563	0.3904	0.2439	0.3314	0.3098	0.3688
1996	0.5052	0.4795	0.2793	0.4017	0.3050	0.3828
1998	0.5760	0.5760	0.3239	0.4794	0.3239	0.4205
2000	0.5433	0.5886	0.3469	0.4979	0.3016	0.3923
2002	0.5556	0.5630	0.2820	0.4556	0.2746	0.3820

Morishima substitution elasticities were calculated by county (Table 14). The most interesting results are the asymmetric elasticities found in several counties. For example, the capital-labor elasticity for Skagit County suggests that these inputs are Morishima substitutes, but the result is reversed with the labor-capital elasticity. The first result can be interpreted as the ratio of capital to labor use increases as wages rise. This can occur if, for example, fewer workers are employed to operate the same capital. With the second elasticity, the ratio of labor to capital use decreases as the price of capital increases suggesting that labor use drops faster than capital use when capital prices rise. This result is particularly evident in Whatcom County.

Table 14. Morishima substitution elasticities by county

County	Capital-Labor	Labor-Capital	Capital-Log	Log-Capital	Labor-Log	Log-Labor
Clallam	0.5596	0.4982	0.1735	0.3712	0.2348	0.3619
Clark	0.5210	0.3742	0.1471	0.2809	0.2938	0.3871
Cowlitz	0.3939	0.6374	0.4358	0.5705	0.1923	0.2592
Grays Harbor	0.2692	0.7883	0.4565	0.6832	-0.0626	0.0424
Jefferson	0.2859	0.5406	0.3754	0.4881	0.1208	0.1732
King	0.3754	0.1319	0.0090	0.0744	0.2525	0.3100
Kitsap	0.0694	0.5369	0.3510	0.4856	-0.1166	-0.0652
Lewis	0.4124	0.4446	0.2749	0.3809	0.2427	0.3064
Mason	0.2248	0.6332	0.4550	0.5823	0.0465	0.0975
Pacific	0.2026	0.7076	0.4844	0.6436	-0.0206	0.0435
Pierce	0.4334	0.4633	0.2845	0.3960	0.2546	0.3218
Skagit	0.4909	-0.5279	-0.6252	-0.6087	0.3936	0.4744
Skamania	0.2789	0.2097	0.0894	0.1607	0.1585	0.2076
Snohomish	0.4230	-0.5024	-0.5601	-0.5640	0.3653	0.4269
Thurston	0.4595	0.4444	0.2334	0.3629	0.2484	0.3300
Whatcom	0.4891	-1.1710	-1.2804	-1.2837	0.3797	0.4924

Own-price demand elasticities--Own-price elasticities reflect the percent change in sawmill demand for an input in response to a one percent change in own-price. Recall that these elasticities are directly proportional to Allen substitution elasticities. Values calculated for labor, logs, and capital own-price elasticities had the expected negative sign, as required by economic theory (Table 15). All own-price demand responses were inelastic; for all inputs, a rise in own-price led to a less than proportionate reduction in the respective factor share of total costs, all else equal. Capital demand was most responsive to own-price changes; log demand had the smallest response to changes in own-price.

Table 15. Regional own-price demand elasticities

	Capital	Labor	Logs
Capital	-0.4506		
Labor		-0.3237	
Logs			-0.1483

Demand for capital became less sensitive to changes in own-price over time (Table 16). Capital own-price elasticity values rose gradually, spiked in 1994 then settled back into a weakly inelastic relationship by 2002 (Figure 23). Labor demand became more price sensitive consistently to 1982 and remained relatively stable afterwards. Log demand was the most inelastic with respect to own-price. Log own-price elasticity was also the least volatile over the study period. Such inelastic log demands translated to greater relative impact on sawmill costs, which were eventually reflected in the input cost shares.

Table 16. Own-price demand elasticities by year

Year	Capital	Labor	Logs
1972	-0.4794	-0.0363	-0.1140
1974	-0.4606	-0.1753	-0.1078
1976	-0.4666	-0.2351	-0.1262
1978	-0.4452	-0.2508	-0.1152
1980	-0.4779	-0.3165	-0.1675
1982	-0.4796	-0.3499	-0.1923
1984	-0.4543	-0.3535	-0.1808
1986	-0.4546	-0.3282	-0.1534
1988	-0.4147	-0.3359	-0.1426
1990	-0.4153	-0.3445	-0.1517
1992	-0.4031	-0.3427	-0.1460
1994	-0.3055	-0.2999	-0.0947
1996	-0.3716	-0.3208	-0.1545
1998	-0.4325	-0.3450	-0.1850
2000	-0.4407	-0.3329	-0.1790
2002	-0.4255	-0.3386	-0.1985

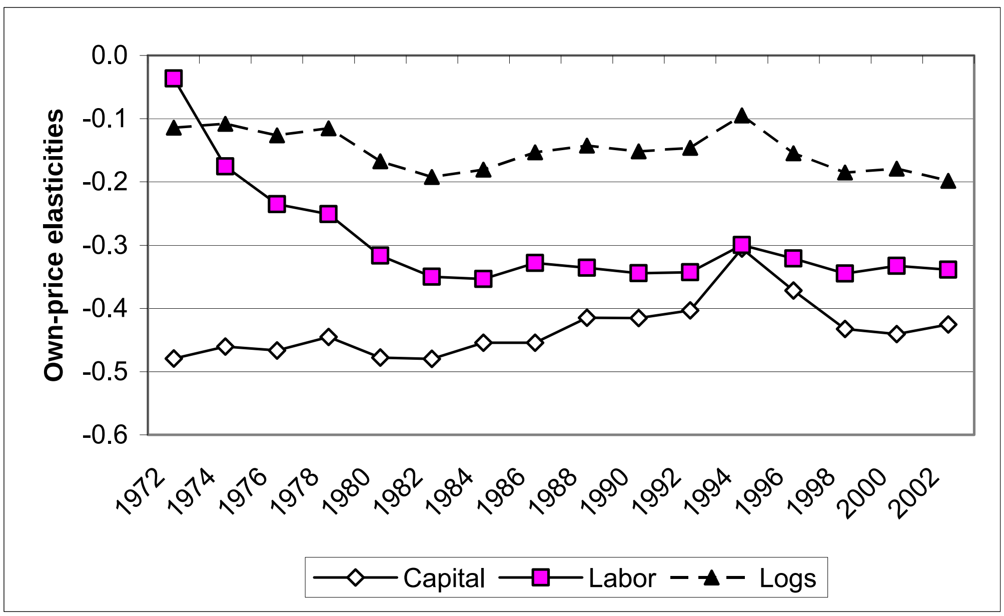

Figure 23. Own-price demand elasticities by year

Own-price elasticities for lumber inputs by county are presented in Table 17. A smaller absolute value means price changes can move a great deal before input use changes. Demand for capital by sawmills was most responsive to own-price changes in most counties. Labor was most inelastic in Kitsap, Mason and Pacific counties. Log demand was most inelastic in Snohomish, Skamania and King counties. Whatcom County continues to raise economic questions with respects to unexpected results.

Table 17. Own-price demand elasticities by county

	Capital	Labor	Logs
Clallam	-0.3335	-0.2523	-0.1472
Clark	-0.2262	-0.3009	-0.1410
Cowlitz	-0.4532	-0.2343	-0.1421
Grays Harbor	-0.4063	-0.1324	-0.1870
Jefferson	-0.4074	-0.1447	-0.1092
King	-0.0531	-0.2337	-0.0976
Kitsap	-0.3107	0.0042	-0.1139
Lewis	-0.3095	-0.2581	-0.1197
Mason	-0.4556	-0.0989	-0.1253
Pacific	-0.4496	-0.0799	-0.1575
Pierce	-0.3460	-0.2533	-0.1185
Skagit	0.5938	-0.3294	-0.1301
Skamania	-0.1292	-0.1534	-0.0856
Snohomish	0.5253	-0.3065	-0.0817
Thurston	-0.3201	-0.2423	-0.1304
Whatcom	1.1946	-0.2508	-0.1526

Cross-price elasticities--Cross-price elasticity of demand indicates how demand for one production input responds to changes in other input prices. Complementary inputs have negative cross-price elasticities; substitutes are positive. Cross-price demand elasticities, like Morishima substitution elasticities, are not symmetric with respect to input combinations.

For the westside Washington region, all values are positive and weakly inelastic, indicating that lumber manufacturers had limited ability to substitute between inputs in response to price changes (Table 18). The capital to labor cross-price elasticity was the largest at 0.2002; demand for capital rose by 0.20 percent for every one percent increase in the price of labor. Labor to capital cross elasticity of demand was slightly lower at 0.1555. The demand for logs was virtually unaffected by any change in capital and labor input prices, while a 1 percent increase in log prices led to 0.25 percent and 0.17 percent increase in capital and labor use, respectively.

Table 18. Regional cross-price demand elasticities

	Price of capital	Price of labor	Price of logs
Capital		0.2002	0.2504
Labor	0.1555		0.1682
Logs	0.0795	0.0688	

Note: The first row indicates how a 1% change in prices of capital, labor and logs effects the demand for capital. The first column indicates the effect of a 1% change in price of capital on the demand for the three inputs.

Table 19 contains cross-price demand elasticity values over time. Capital-labor and labor-capital cross-price elasticities were positive for all years, reaffirming their relationship as substitutes in lumber production (Figure 24). Labor price changes impacted capital demand more than log demand. Capital demand increased about three times as much as log demand in response to rising labor wages throughout most of the study period. Labor and capital demand responded differently to changes in log prices, with capital acting as less of a substitute over time, and labor remaining quite inelastic.

Table 19. Cross-price demand elasticities by year

Year	Capital-Labor	Labor-Capital	Log-Capital	Capital-Log	Labor-Log	Log-Labor
1972	0.0955	0.1827	0.1424	0.3838	-0.1464	-0.0284
1974	0.1211	0.1522	0.1022	0.3395	0.0231	0.0055
1976	0.1441	0.1663	0.1065	0.3225	0.0688	0.0197
1978	0.1466	0.1422	0.0838	0.2986	0.1086	0.0314
1980	0.1997	0.2011	0.1186	0.2781	0.1153	0.0488
1982	0.2570	0.2149	0.1115	0.2226	0.1350	0.0808
1984	0.2670	0.1656	0.0690	0.1872	0.1879	0.1117
1986	0.2066	0.1604	0.0819	0.2480	0.1678	0.0714
1988	0.2105	0.1304	0.0544	0.2042	0.2055	0.0883
1990	0.2272	0.1323	0.0516	0.1881	0.2122	0.1000
1992	0.2212	0.1253	0.0470	0.1819	0.2173	0.0990
1994	0.1563	0.0848	0.0259	0.1492	0.2151	0.0688
1996	0.1843	0.1079	0.0301	0.1247	0.1504	0.0619
1998	0.2311	0.1436	0.0470	0.1389	0.1389	0.0756
2000	0.2104	0.1478	0.0571	0.1678	0.1226	0.0594
2002	0.2169	0.1375	0.0302	0.0835	0.0761	0.0433

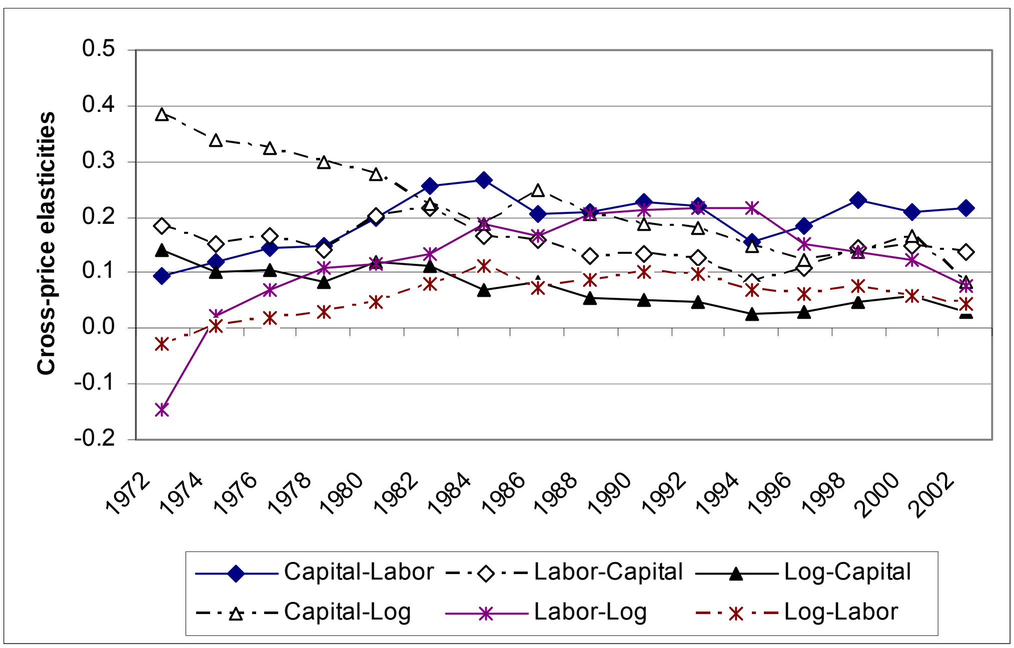

Figure 24. Cross-price demand elasticities by year

Input cross-price elasticities by county are presented next (Table 20). Capital and labor cross-price elasticities were positive, indicating they were substitutes in all cases. Logs and labor exhibited both substitute and compliment input behavior. These inputs acted as compliments in Grays Harbor, Kitsap, Mason, and Pacific counties. Increases in the cost of capital led to greater use of labor in all counties, whereas the demand for logs fell with greater capital costs in Skagit, Snohomish and Whatcom counties. Increases in log prices led to different behavior in capital and labor use depending on the county. Higher log prices reduced capital use in King, Skagit, Snohomish, and Whatcom counties. Higher log prices reduced labor use in Grays Harbor, Kitsap, Mason, and Pacific counties.

Table 20. Cross-price demand elasticities by county

County	Capital-Labor	Labor-Capital	Log-Capital	Capital-Log	Labor-Log	Log-Labor
Clallam	0.3073	0.1647	0.0376	0.0262	0.0876	0.1096
Clark	0.2200	0.1481	0.0548	0.0061	0.1528	0.0862
Cowlitz	0.1596	0.1841	0.1173	0.2937	0.0502	0.0249
Grays Harbor	0.1368	0.3820	0.2770	0.2695	-0.2496	-0.0900
Jefferson	0.1412	0.1332	0.0808	0.2662	0.0115	0.0284
King	0.1417	0.0788	0.0213	-0.0887	0.1549	0.0763
Kitsap	0.0736	0.2263	0.1749	0.2371	-0.2304	-0.0610
Lewis	0.1543	0.1350	0.0714	0.1552	0.1230	0.0483
Mason	0.1260	0.1776	0.1267	0.3297	-0.0788	-0.0014
Pacific	0.1228	0.2579	0.1939	0.3269	-0.1781	-0.0364
Pierce	0.1800	0.1173	0.0500	0.1659	0.1360	0.0685
Skagit	0.1615	0.0659	-0.0149	-0.7553	0.2636	0.1449
Skamania	0.1254	0.0805	0.0314	0.0038	0.0729	0.0542
Snohomish	0.1164	0.0229	-0.0387	-0.6418	0.2836	0.1204
Thurston	0.2171	0.1243	0.0427	0.1030	0.1181	0.0876
Whatcom	0.2384	0.0237	-0.0891	-1.4330	0.2271	0.2417

Technical change--Hicks-neutral technological change was rejected for western Washington lumber manufacturing. Slopes of production isoquants were not independent of the state of technology, meaning that technical change altered the optimal combination of production inputs over time. Evaluated at the mean of 256 observations, the regional rate of technical change was 0.084. Thus, technical change actually increased westside Washington lumber production costs by 8.4 percent every two years. This result was unexpected and may be related either to the use of the time trend proxy or the autocorrelation correction applied to the model. Results over time and by county were equally nonsensical and so are not reported here. Technical change bias was calculated for the westside region only. Technical change was capital and labor using and log saving, with values of 0.0728, 0.0195, and -0.0311, respectively.

7.3 Comparison of Cobb-Douglas and Translog Results

One goal of this study was to compare the robustness of results to the selection of functional forms. Because of the lack of second-order terms in the Cobb-Douglas model, comparisons were limited to input factor demand equations, economies of scale/ linear homogeneity, and regional demand elasticities.

Input factor demand results in Table 21 display the mix of inputs for both models. Models agreed that logs dominated lumber manufacturing costs over the study period, with labor and capital costs second and third, respectively. The magnitude of values differed somewhat. The Cobb-Douglas cost function estimated that about 73 percent of sawmill total costs were attributed to log inputs, while logs comprised only about 58 percent of costs using the translog cost function. The translog estimated labor and capital cost values of 24 and 18 percent, compared to 17 and 14 percent for the Cobb-Douglas, respectively.

Table 21. Factor demand comparison

Parameter	Cobb-Douglas regression coefficient*	Translog mean cost shares
β_L	0.1656** (0.0236)	0.2368
β_S	0.7288** (0.0564)	0.5793
β_K	0.1422** (0.0195)	0.1839

** 99% significant

Own- and cross-price demand elasticities from the Cobb-Douglas and the translog forms appear in Table 22. Translog values are in parentheses. Own-price elasticities on the diagonals show that results generally agreed but values were more elastic using the Cobb-Douglas. Cross-demand elasticities are positive in all cases, indicating agreement that capital, labor, and logs were substitutes. Values were greater using the translog for capital-labor, capital-log, and labor-log cross-price elasticities. The magnitude of difference between the remaining input pairs is noteworthy, especially for logs.

Table 22. Own-and cross-price demand elasticity comparison

	Price of capital	Price of labor	Price of logs
Capital	-0.8578	0.1422	0.1422
	(-0.4506)	(0.2002)	(0.2504)
Labor	0.1656	-0.8344	0.1656
	(0.1555)	(-0.3237)	(0.1682)
Logs	0.7288	0.7288	-0.2712
	(0.0795)	(0.0688)	(-0.1483)

Both models were used to compute economies of scale. Using the Cobb-Douglas functional form, constant scale economies and therefore linear homogeneity could not be rejected. This result helped to validate the linear homogeneity restriction imposed on the benchmark translog model.

Although these results point to robustness to the choice of functional form to impose on the cost function, one observation stands out. Among other restrictions, the translog form rejected the Cobb-Douglas specification of unitary elasticity of substitution. This meant that the Cobb-Douglas form was inappropriate to apply to the lumber production data, no matter how nicely results agreed with the translog form.

8. Discussion

The translog functional form with linear homogeneity and symmetry in input prices appears to be an appropriate model for western Washington lumber production. Restrictions for no technical change, Hicks-neutral technology, homogeneity, homotheticity, and unitary elasticity of substitution were all rejected. However, estimates of technical change proved to be contrary to expectations.

Restrictions of homogeneity and homotheticity of the cost function were also rejected. A cost function corresponds to a homothetic production function only if the cost function can be expressed as separable in output and input factor prices. A homothetic cost function is further restricted as homogeneous if the elasticity of cost with respect to output is constant. Rejection of these assumptions meant lumber manufacturing costs were not independent from output; costs did not change proportionally when input prices changed or when lumber production levels changed. The isoquants of the production function were not parallel with respect to the origin; output changes in western Washington sawmills led to changes in factor proportions.

Rejection of unitary elasticity of substitution provided evidence that significant degrees of input substitution occurred over the study period. Rejection also implied that specifying lumber production with a Cobb-Douglas cost function is not appropriate. Thus, it is inappropriate to apply a fixed-factor model structure to study lumber production in western Washington.

8.1 Economies of Scale

Economies of scale were calculated for the westside Washington regionally, biennially, and for each westside county. For the regional panel set, economies of scale were measured at 0.418, meaning that every one percent increase in output reduced lumber costs by 0.42 percent. The value indicates that overall, westside mills enjoyed returns to scale over the study period. Furthermore, should demand increase, some reductions in costs are likely.

Economies of scale varied when viewed over time. The sharp increase in economies of scale from 1978 to 1982 coincided with the period of a sharp drop in lumber prices in 1979 followed by a recession in 1982. Rising costs in log markets and reduced consumer demand with a corresponding reduction in product prices forced lumber production to fall, heralding a period when the opportunity to reduce costs grew as lumber output fell. From 1982 until 1994 scale economies fell, implying that firms captured cost savings opportunities as demand grew by expanding production throughout this period.

The county-level perspective provided an additional geographic dimension to economies of scale. Relatively low values suggest that counties such as Snohomish may have less opportunity to gain scale economies, perhaps since mills have taken advantage of scale economies over most of the study period. To contrast, counties with relatively high values like Jefferson have greater opportunities to reduce costs by expanding production should demand exist.

There appears to be a relationship between county location and scale economies. Most of the counties with unexploited economies of scale were located on the Olympic Peninsula. These counties historically were centers of specialty product manufacturing, such as cedar shingles and shakes and large dimension beams. In addition, Olympic Peninsula mills traditionally had access to supplies of both private and public timber representing a wide spectrum of log sizes, shapes, and quality that was not conducive to large scale lumber production. Mills primarily expanded production by retooling to maximize output of commodity grade lumber from a relatively homogeneous supply of logs. However, many mills on the Olympic Peninsula serving specialty markets never made this transition because they did not compete with commodity producers or have reliable access to a homogeneous log supply.

Another aspect of location associated with scale economies may be access to transportation networks. The nine counties containing segments of U.S. Interstate 5 (I-5) have the lowest scale economies, with the exception of Skamania, Mason and Whatcom counties. Although ocean access may also be a factor, it was not possible to tease out the influence of ports because every county contains at least one port facility. In addition, most newer capacity in western Washington was installed in counties near to the I-5 corridor, highlighting the interaction between transportation and capacity.

8.2 Elasticities

Substitution and demand elasticities provide clues to the behavior of the western Washington lumber industry. Regional Allen and Morishima substitution elasticities agreed that westside mills most readily substituted between capital and labor. The Allen value of 0.8455 implied the substitution possibility was greater than the Morishima values, but both agreed the relationship was inelastic. Morishima elasticities showed that capital was substituted for labor more easily than labor for capital. This provides evidence that lumber manufacturing jobs were relatively easier to replace with sawmill real property investments than the converse.

At the opposite end of the spectrum, the Allen and Morishima elasticities affirmed that mills had less success in substituting away from logs. The Allen log-labor substitution elasticity of 0.2904 showed little potential for substitution between log inputs and sawmill employment. Morishima elasticities agreed that substituting logs for labor was inelastic and additionally that logs were a weaker substitute for labor. This input combination had the least flexible potential for substitution in sawmill production technology. The log-capital Allen value of 0.4322 indicated modest substitution possibilities between logs and capital investment. Morishima elasticities showed that firms could substitute capital for logs, but substituting logs for capital was more difficult. This result suggests that mills were more likely to invest in capital infrastructure when faced with rising log prices than vice versa.

Regional level own-price and cross-price demand elasticities reinforced the difficulty sawmill operators had responding to changing log costs. Logs were highly own-price inelastic; large changes in log price had little impact on log demand. This implied that mills had little flexibility and were virtually powerless to change production strategies when faced with any unexpected rise in log prices. Cross-price demand elasticities showed the demand for logs was unresponsive to changes in capital and labor prices, again demonstrating the necessity of logs to lumber manufacturing. This conclusion was intuitive; a firm may lay off workers or postpone investment in facilities when faced with rising costs, but it is impossible to create lumber without wood.

Examination of Allen, Morishima, own- and cross-price elasticities over time led to some additional insights. Biennial Allen and Morishima substitution elasticities indicated that firms were most able to substitute between capital and labor throughout the study period. Log-capital substitution declined over time as the two inputs became more complementary in the production process. Labor and logs began with almost no substitution potential; log use could not rise without adding more workers and vise versa. This relationship decoupled somewhat around 1980, but the two inputs remained weak substitutes. Results suggest that mills restructured in response to the early 1980s recession (a demand driven shock) primarily by using capital in place of labor. Capital was also used in place of logs, but the substitution potential was more limited. Mills had little ability to respond to timber supply constraints in the 1990s (a supply driven shock) because of reduced ability to substitute between capital and labor and labor and logs. Declining log exports after 1996 likely drove log-capital and labor-log substitution elasticities to become more complementary as increased log supply led to increased demand for workers and capital.

Over time, own-price demand for logs remained highly inelastic, again reflecting the lack of flexibility mill owners had to respond to fluctuating log prices. Log own-price response in periods of known market perturbations was almost imperceptible. On the other hand, capital own-price elasticity exhibited some sensitivity to changing market conditions; it began rising during the mid-1980s and jumped to its most inelastic value in 1994. The subsequent rise in capital own-price elasticity may have resulted from mills shifting away from capital investment as more log volume became available. Labor demand was least responsive to own-price changes early in the study period but flattened by 1986, suggesting employment levels became easier to adjust after industry restructuring in the 1980s.

Cross-price elasticities over time indicated that mill demand for capital became more responsive to labor price changes and less responsive to log price changes during the early 1980s. Capital-labor cross price elasticity peaks in 1994 and 1998 suggest that capital investment responded most readily to labor price changes during periods of timber supply volatility. Capital-log cross-price demand was moderately elastic but declined over time, approaching zero by 2002. The relationship between labor and logs was the most stable; the impact of labor costs on log demand was most pronounced between 1984 and 1996.

Elasticities calculated at the county level provided a glimpse of lumber production decisions at a finer geographic scale than reported in any previous study. Allen and Morishima elasticities showed that sawmills in Grays Harbor, Clallam, Pacific, and Cowlitz Counties had the greatest potential for substitution between capital and labor. This implied that mills in those counties made investments in capital improvements that employed fewer workers. The remaining counties also were able to substitute between capital and labor, except for Whatcom and Snohomish, where Morishima elasticities placed capital and labor as highly elastic complementary inputs.

Capital and log substitution rates displayed a weaker regional pattern than seen above. Grays Harbor, Mason, Pacific, and Cowlitz Counties had the highest Allen and Morishima values. Substitution elasticity values for the remaining counties on the Olympic Peninsula, along with a few in other regions, suggested these counties made capital investments to substitute away from logs. In contrast, capital and logs in Whatcom, Skagit, and Snohomish sawmills were elastic Allen complements; capital investments were associated with greater log use. Morishima results agreed with Allen elasticities and also showed that producers had a greater propensity to substitute capital for logs than logs for capital.

Allen and Morishima labor-log substitution elasticities by county had a reversed trend from previous elasticity measurements. Allen substitution values showed Grays Harbor, Kitsap, Mason, and Pacific County mills used these inputs as complements. Labor and logs were substitutes in the remaining counties. The greatest ability to substitute between labor and logs occurred in Whatcom, Skagit, and Snohomish Counties. Morishima values confirmed this finding, and showed that lumber producers had consistently greater ease in substituting logs for workers than workers for logs.

County-level capital own-price demand elasticity calculations for three counties, Skagit, Snohomish, and Whatcom, resulted in positive values that violated economic theory. The issue possibly originated in the input cost share data that form the basis for elasticity calculations. The average capital share of total costs in these three counties was eight, five, and four percent, respectively. Recall that capital costs are based upon the real property assessed values of sawmills according to County Assessor records. The low proportion of capital costs (low capital intensity) in these counties seems to be a function of the age of mills. All three counties had the same mills in operation for all or most of the study period, indicating that depreciation may have impacted assessed values of structures. This may explain why Snohomish and Whatcom County sawmills consistently had such different substitution elasticity values from the remaining counties as well. Capital demand in Mason County had the greatest own-price response.

Labor own-price demand elasticity was fairly consistent across counties. Most counties had values between -0.2 and -0.3. One diverging result was the 0.0042 own-price elasticity of demand for labor in Kitsap County mills, which although very close to zero, is still in violation of economic theory. Recall that all findings for Kitsap County were based upon data from one large mill that shut down operations in 1995. The lack of wage sensitivity suggested the presence of monopsony behavior consistent with "company towns" where labor markets are isolated and dependent upon one employer.

The trend that log demand was highly inelastic with respect to changes in own price observed at regional and biennial scales was evident at the county level as well. Log own-price elasticities varied from -0.1870 in Grays Harbor County to -0.0817 in Snohomish County, values so close to zero they are hardly worth getting excited about.

Cross-price demand elasticities by county indicated that the impact of capital price on demand for labor was strongest in Clallam, Clark, and Thurston County sawmills. Labor demand was most responsive to capital price changes in Grays Harbor, Kitsap, and Pacific County mills, indicating a geographic trend that may again be attributable to low assessed values of mills compared to labor costs in those counties. Capital and labor were substitutes in all counties, which was not the case for the relationship between log inputs with capital and labor.

Demand for logs was virtually non-responsive to changes in capital price in all counties. Although log-capital cross-price demand was complementary in counties, values were near zero. Demand for capital was more responsive to changing log prices overall, with King, Skagit, Snohomish, and Whatcom counties exhibiting complementary behavior. Investments in mill infrastructure in these counties led to greater material use, because increasing demand for capital led to increased demand for logs. This also suggests that rising log prices reduced demand for capital investment.

Labor-log and log-labor cross-price demand was complementary in Grays Harbor, Kitsap, Pacific, and Mason County mills. Cross-price demand was weakly elastic in the rest of the region. These results show that markets for labor and logs were interconnected; a price shock in logs not only affected log demand, it reduced demand for workers. One explanation may lie in the lack of alternative employment opportunities for workers in these counties. Perhaps less skilled mill workers had little choice but to accept being hired to work during boom periods and subsequently laid off during market downturns.

8.3 Technical Change

The estimates of technical change proved to be contrary to expectations. There are a variety of implications from this result. Rejection of the no technical change restriction provides evidence that costs changed significantly over time. The rate of technical change was estimated at 0.084 per biennium for the lumber industry, an unexpected positive value, possibly due to the use a time trend as proxy for technology. Increased productivity in mills, as evidenced by improved lumber recovery factors over the study period, may have confounded this result as mills were able to produce more lumber from the same volume of log input. Autoregressive corrections to time series data may have also contributed to the result. Rejecting Hicks-neutral technology implies that as technology changes, the mix of production inputs changes. Technical change was capital- and labor-using and log-saving, indicating that capital investment in mills and the use of more labor increased at the expense of logs.

8.4 Policy Implications

On average the lumber industry in western Washington exhibited increasing returns to scale and technological change over the study period. However, results suggest that scale economies had declined by 1998. These results suggest that the adoption of capital-using innovations may have declined over time (Lundmark, 2005). Future policies encouraging investments that expand or replace old sawmills with modern and more productive ones may have limited value for reducing costs.

In addition, policies aimed at stimulating capital demand may not increase sawmill employment. Elasticity results show that capital and labor were substitutes and that demand for capital was most sensitive to own-price changes. Substitution elasticities show western Washington mills were most successful at substituting between capital and labor. Cross-price elasticities show rising labor prices led to increased demand for capital. Substitution and price elasticities suggest that policies impacting capital prices may have little consequences for expanding sawmill employment.

Sawmills appear to have benefited from the channeling of export logs back into domestic processing facilities. This new source of raw materials may have alleviated fears of resource scarcity guiding mill decisions following timber supply shocks in the early 1990s. The increased availability of logs appears to have driven capital investment in new capacity and record lumber production levels observed by 2002.

If promoting healthy forest-dependent communities and rural employment is a policy goal, the trend of new large capacity sawmills locating near the I-5 corridor and away from rural areas should concern policymakers. The role of lumber manufacturing in rural development as a potential for generating employment appears to have diminished. However, Lee and Jennings-Eckert (2002) found that between 1964 and 1997, small- and medium-sized sawmills provided the most stability in employment during periods of both long-term growth and decline in the forest products industry in Washington. Improving the operating environment for small mills may be one approach to stabilizing wood-producing communities. Policies such as providing access to limited supplies of state and federal timber, providing favorable credit and taxation, and reducing the disproportionate impacts of environmental regulations on small mills might help create jobs and maintain steady employment opportunities in rural areas.

This study shows that log costs were the largest share of sawmill production costs. When log prices rise, western Washington mills have almost no flexibility to respond by substituting lower cost inputs. Since log prices contribute most significantly to rising sawmill costs, firms were highly sensitive to unexpected changes in log markets. Policies that reduce timber harvesting, encourage land-use conversion, or increase transportation costs can impact log prices and, with no change in product demand, reduce sawmill profits enough to trigger mill closures, especially during times of market contraction.

Given that public lands are expected to contribute relatively little to future western Washington timber supplies, the majority of timber harvesting will occur on private lands. There is concern that harvest from non-industrial lands will decrease as landowner preferences shift away from the financial gain associated with harvested timber to alternative land uses (McQueen and Potter-Witter, 2006). Declining harvest rates and higher logging costs could lead to closure of those mills with the least ability to substitute capital for wood.

Land conversion and parcelization of forest land holdings impact log costs by raising the cost of harvesting. The population in Washington is expected to increase from 6.50 million in 2006 to 7.46 million by 2015, putting additional development pressure at the wildland-urban interface (Washington State Office of Financial Management, 2007). With evidence that the land base of suitable timber in western Washington is shrinking; policies that help manage growth and mitigate increasing timber scarcity are likely to benefit the lumber industry.

The rising cost of transportation introduces higher harvesting costs that are passed on to timber owners. Elasticities showed that while capital investment may reduce log costs, increased lumber recovery may come at the expense of sawmill workers. Another option is to examine policies that reduce transportation costs for delivering logs from the forest to the mill or delivering lumber from the mill to product markets. Mill capacity is increasingly being located away from logging sites; with rising fuel prices, mills may benefit from incentives to utilize alternative fuels or modes of transportation, such as water and rail.

8.5 Study Limitations

There were several study limitations encountered including issues surrounding use of the translog cost function, estimation techniques, and specific problems with data required for the lumber cost model.

The translog cost function is a second order local approximation to an arbitrary cost function describing the underlying production structure in western Washington sawmills. Because the translog is an approximate cost function, it only satisfies the concavity and monotonicity properties of the cost function locally. Since the translog was developed as a local approximation to the true underlying cost function, it may give misleading results when applied globally. The estimated translog cost function must be tested at every observation to ensure regularity conditions and curvature properties hold. Thus, the translog functional form yields unrestricted parameter estimates, but at the cost of possibly violating global the concavity and positivity conditions required for a well-behaved cost function.

Another problem with the translog is that the large number of parameters can lead to problems with degrees of freedom if the data set is small. This was not an issue with the panel data set, which contained 256 observations. However, attempts to use the translog to estimate production behavior for the western Washington, rather than the panel data set, were not successful because there were only 16 observations to estimate 21 model parameters, leading to an identification problem. Subsequent calculations of scale economies, elasticities, and technological change at the regional, temporal, and county-level scales used the same translog coefficients with the mean of values for the entire region, each period, and each county, respectively.

Data from the WADNR Mill Survey led to additional problems concerning the heterogeneity of reporting mills. Data from integrated and mini-mills, public traded and privately owned mills, and mills that produce specialty products or a heterogeneous mix of lumber output were pooled even though these mills employ different technologies. In addition, lumber output data included all species, including hardwood and cedar that may have different production structures from Douglas-fir and hem-fir softwood lumber. Because the smallest unit of aggregation for labor data is SIC/NAICS category by county, it was impossible to structure the data set to analyze a more homogeneous industry.

Last, the lack of firm level capital data is another limitation of the model. The translog works well for industries or nations that collect capital investment information from producing entities. Otherwise, applying the translog (other any other production function) means developing a proxy measure for capital price and quantity, which introduces error in the estimation results. For example, monopolist industries subject to governmental reporting requirements, such as energy and telecommunications, have much better firm level data available than firms operating in competitive markets that encourage confidentiality to maintain competitiveness. In addition, nations such as Canada and Norway that operate under a more socialist form of government with public ownership of most forestland have better capital data since sawmills are compelled to report capital investments.

9. Conclusions

The lumber industry in western Washington navigated an amazing array of challenges between 1972 and 2002. The test of the early 1980s recession was met by industry-wide advances in technological innovation and efficiency. Resource availability constraints following timber harvest reductions appear to be abating as millions of additional board feet were channeled into domestic sawmills for processing rather than exported to the Pacific Rim. This phenomenon, along with land use change from forestland conversion, appear to be the next challenges facing the industry and may guide future research efforts into lumber production structure.

This study shows the western Washington lumber manufacturing sector can be modeled with nonconstant returns to scale, nonunitary elasticity of substitution, and biased technical change among the production inputs of capital, labor, and logs. For additional conclusions, the research questions listed at the beginning of this study are individually addressed.

- **Were results robust to the choice of production models?**

  Results using the Cobb-Douglas and the translog functional forms are robust, but translog rejects Cobb-Douglas restriction of unitary elasticity of substitution. Substantial substitution possibilities between factors of lumber production exist, and a fixed-proportion production structure like the Cobb-Douglas is inappropriate to model the lumber industry structure.

- **Did the lumber production function meet required curvature assumptions?**

  A well-behaved cost function is concave in input prices with strictly positive output demand functions. Tests of the lumber data set showed the concavity condition was met in all but two cases; the Hessian matrix of second-order partial derivatives was symmetric and negative semi-indefinite. The requirement that the demand functions be strictly positive was satisfied for each biennial observation as well; translog cost shares were positive at all points. Therefore, the estimated translog cost function was well-behaved, meaning it was an appropriate choice of functional form for the western Washington lumber industry.

- **Was the proportion of capital, labor, and log production inputs fixed?**

  Lumber production costs are most sensitive to the price of logs, followed by the price of labor and were least impacted by the price of capital. Mean cost share values for logs, labor and capital are 58, 24 and 18 percent, respectively. Rejection of the Cobb-Douglas functional form is a rejection of fixed factor production structure.

- **Did lumber producers enjoy increasing returns to scale economies?**

  At the regional level, sawmills have experienced economies of scale in the production of lumber. A 10 percent increase in scale resulted in a 1.18 percent reduction in costs. Economies of scale values jumped during the 1980s recession as firms produced radically less output and faced higher input costs then subsequently declined as firms exhausted scale economies during times of harvest level reductions. There were almost no unexploited economies of scale by the end of the study period. Sawmills in Snohomish, Lewis, King, Skagit, and Pierce counties were most able to take advantage of economies of scale.

- **Were inputs substitutes in the lumber production process?**

  Allen and Morishima partial elasticities of substitution at the regional level agreed that all inputs were inelastic substitutes with the greatest substitutability between capital and labor and least substitutability between logs and labor. Policies encouraging large mills at the expense of smaller mills may have resulted in capital substitution for labor.

Capital and labor were substitutes in every period. Logs and capital started as moderate substitutes but became more complementary over time. Substitution rates declined in response to the 1980s recession and with timber supply constraints in the 1990s. Labor and logs started as strong complements, but Allen Elasticity of Substitution (AES) rose continuously and the inputs became substitutes in 1974 then flattened after a peak in 1984. After 1996, labor and logs AES began to fall; declining log exports may have contributed to the switch.

Sawmills in Grays Harbor, Clallam, Pacific, and Cowlitz Counties had the highest capital-labor substitution elasticity values. Log-capital AES was greatest in Grays Harbor, Pacific, Mason, and Cowlitz; logs and capital were complements in Whatcom, Snohomish, Skagit, King, and Clallam Counties. Labor and logs were the strongest substitutes in Whatcom, Skagit, and Snohomish County mills and complements in Grays Harbor, Kitsap, and Pacific Counties.

Regional MES also showed all inputs as inelastic substitutes. Morishima Elasticity of Substitution (MES) measures are not symmetric like the AES and suggested that lumber producers found it easiest to substitute capital for labor, labor for capital, and capital for logs and most difficult to substitute logs in place of labor.

MES showed a weaker substitution response for capital-labor and labor-capital inputs in response to the early 1980s recession and from the public timber supply shocks around 1994 than the AES. Capital-log and log-capital MES values followed a similar pattern of response to these market shocks. Labor-log and log-labor MES began as complementary, changed to substitutes in response to the recession, and remained modest substitutes at the end of the study period.

Capital was easiest to substitute for labor in Clallam, Clark, Skagit, and Whatcom County mills. Labor was most substitutable for capital in Grays Harbor, Pacific, Cowlitz, and Mason County mills; the inputs were complements in Whatcom, Skagit, and Snohomish County mills. Capital for log substitution potential was greatest in Pacific, Grays Harbor, Mason, and Cowlitz County mills; the relationship was complementary in Whatcom, Skagit, and Snohomish Counties. Labor-log substitution was modest overall but most prevalent in Skagit, Whatcom, and Snohomish mills.

- **Was demand for inputs responsive to changes in input prices?**

  Regionally and at the county level, capital demand was the most own-price elastic and the cross-price elasticity of demand was greatest between capital and labor inputs. Demand for logs was highly inelastic with own-price elasticity near zero and thus not responsive to price changes. All cross-price demand elasticities including logs were near zero. This pattern was relatively consistent across time and across counties, although at finer scales greater evidence of complementary between inputs was noted.

- **Did firm behavior differ by location and over time?**

  The expansion of lumber production and capacity toward the end of the data period primarily occurred in Lewis, Pierce, Clallam, and Cowlitz Counties owing to new sawmill infrastructure. Gains in Cowlitz County were primarily made from investments in existing mills, especially in 2000. Lewis gained one large mill in 1998, increasing the total number of large mills to seven, but additions in existing sawmills contributed to increase capacity. The number of large mills in Pierce County remained consistent from 1996 to 2002, but again, capacity investments in existing mills led to increased lumber output. Although sawmills in Snohomish County also invested to increase capacity, the loss of three large mills between 1998 and 2002 caused an overall decline in lumber production. These results point to developing processing capacity centers in two areas, Clallam County on the Olympic Peninsula and counties along the I-5 corridor located south of King County. Restructuring of log export markets, proximity to Interstate-5, and port access seem to be factors in industrial expansion, but the magnitude is unknown.

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