Primal and Dual Models of Market Power: An Application to Eastern Oregon's Lumber and Stumpage Markets

by

C. Duncan Campbell

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Doctor of Philosophy

Completed March 18, 1996
Commencement June 1996

AN ABSTRACT OF THE THESIS OF

C. Duncan Campbell for the degree of Doctor of Philosophy in Economics presented on March 18, 1996. Title: Primal and Dual Models of Market Power: An Application to Eastern Oregon's Lumber and Stumpage Markets.

Abstract Approved: ____

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The first objective of this research is to develop primal and dual models of firm behavior that incorporate firms' conjectures of their market power positions. The second is to empirically test for the presence of market power in eastern Oregon's stumpage and lumber markets. Eastern Oregon was chosen since it has historically been a relatively self-supplied stumpage region, mostly from public lands, and because much of the supply contains tree species that possess characteristics that allow for the production of unique products. Additionally, supply will likely increase in the future as public land management agencies implement plans to restore ecosystem health to the region.

The model development and estimation methods use the procedures of the relatively new discipline called the "new empirical industrial organization" (NEIO). NEIO uses theoretical results of profit maximizing behavior to econometrically estimate the amount by which industry behavior deviates from perfect competition. In particular, this research utilizes input and output shadow prices to derive firms' conjectural elasticities, which are then directly estimated using nonlinear two-stage and three-stage least squares.

The results of the empirical estimations, although not conclusive, indicate that competitive market outcomes can not be rejected in eastern Oregon's lumber and stumpage markets. The results are as hypothesized for the output market and are consistent with prior studies of Pacific Northwest stumpage markets.

Care should be taken however, in interpreting the results. Since annual time series data are used the results are averages over the estimation period. If the competitive behavior in the markets is changing the results may not capture the latest structure. Additionally, since logs have historically been processed near to where they have grown, an area the size of eastern Oregon may contain numerous supply areas. The estimation results are the average behavior of all the markets. The industry-level data also requires restrictive assumptions on firm behavior. A preferred analysis would use firm-level data, which would likely decrease the standard errors and provide more consistent results.

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APPROVED:

Major Professor, representing Economics

Head of Department of Forest Resources

Dean of Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

C. Duncan Campbell, Author

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INTRODUCTION

Stumpage and wood products markets are often characterized by many sellers of timber and purchasers of wood products and few buyers of stumpage and producers of wood products, thus endowing the buyers of stumpage and sellers of wood products with market power. The results are lower input prices for timber sellers and higher output prices for wood products purchasers than would be the case under a competitive market structure. The resulting price distortions precipitate an inefficient allocation of resources, which forces society to a lower level of utility than would be the case under competition. The lower price in the input market also discourages investment in the production of the input, and when the timber is owned by the public through agencies like the U.S. Forest Service, it becomes the public who isn't receiving a fair price for its resource.

While numerous studies have examined the issue of competitive performance in stumpage and wood products markets (Ireland 1976, Mead 1966, Mead et. al 1981, Haynes 1979, 1980a, 1980b, Johansson and Löfgren 1983, Weiner 1969, and Murray 1992), only a few have utilized methods that include procedures that contain explicit tests for empirical validation. The objective of this research is to employ procedures from the relatively new discipline called the "new empirical industrial organization" (NEIO) to develop and empirically apply econometric models that explicitly test for the presence of market power in stumpage and wood products markets.

MARKET POWER IN STUMPAGE MARKETS

There is a public perception that "the U.S. Forest Service through long tradition, political intervention and close working relationships between purchaser and seller, has consistently sold timber under rules that favor the industry" (Durbin 1991). While the Forest Service has a myriad of reasons for selling timber, among which are: the desire for economic development and community stability, the need for forest access, the reduction of forest waste and hazard, and the salvage of damaged timber; they are mandated to sell timber at its "fair market price," which is defined as "the price acceptable to a willing buyer and seller, both with knowledge of the relevant facts and not under pressure or compulsion to deal.[1]" The intent of this is to protect the agency against inadequate competition and collusion (Clawson and Held 1957).

Even in areas where the Forest Service is not a major supplier of stumpage, the issue of competitive performance is of interest. Logs have a relatively low value per unit of weight, therefore, they are typically processed near where they are grown. The increased distances that mills are now transporting logs has resulted from the changing structure of the industry that is being brought about by the reductions in timber supply due to stricter environmental laws intended, among other things, to protect biodiversity. The consolidations that are happening in the industry and the economies of scale that are producing newer, highly mechanized, capital-intensive mills are allowing logging to be spread over larger landscapes. This is a trend that Jim Geisinger, president of the Northwest Forestry Association, thinks will continue. He believes that "there will be many

[1] "Forest Service Handbook," U.S. Forest Service, sec. 2423.12.

fewer players in the industry [and] the companies that will still be there will be larger..." (Sonner 1994).

Therefore, the area in which logs can be economically transported, whether small or large, usually contains only a few buyers. A market with a few buyers is termed an oligopsony; if there is only one buyer the term is monopsony. Oligopsonies and monopsonies are perceived as undesirable since the firm(s) may exert market power and create an inefficient allocation of resources.

A market structure where all the economic agents are price takers is described as "perfectly competitive" and "economically efficient". The individual demand and supply curves the economic agents face for inputs and outputs are infinitely elastic. The outcome of this type of market arrangement is said to be economically efficient in the sense that resources (factor inputs) are allocated between alternative uses until the marginal benefit of further allocation is exhausted (equals marginal cost) and consumer plus producer surplus is maximized.

When economic agents recognize that their input and/or output decisions affect market outcomes (their supply and/or demand curves are no longer infinitely elastic) they are no longer price takers. The market outcomes when firms incorporate this market power position in their decision calculus are no longer economically efficient.

Figure 1 shows a simple supply and demand framework for a factor of production. If this market were perfectly competitive, output for the input would be Q_c -- that is, production would occur where supply and demand intersect and the price or wage rate for that factor would be P_c. Each firm would be able to purchase or hire as much of the input

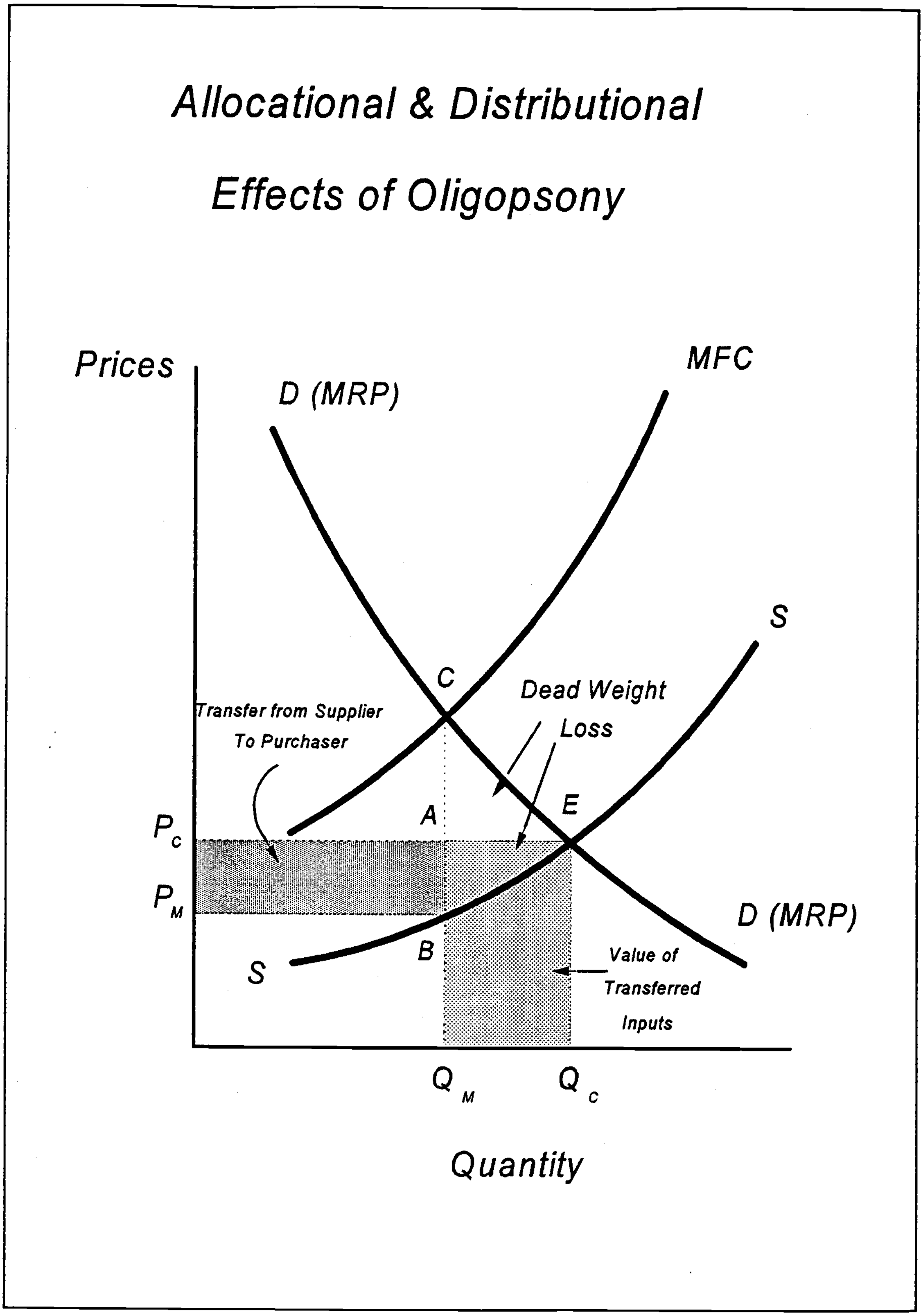

Figure 1 Allocational and Distributional Effects of Oligopsony

at this price as it wanted. Under a monopsony or oligopsony, however, the firms are not price takers for the inputs they buy. That is, the supply curves faced by the individual firms are not infinitely elastic at the prevailing price. It is frequently necessary for the firms to offer a higher price for a factor than is currently prevailing if it is to acquire more of the factor. This will require paying a higher rate not only for the additional "marginal" unit but for all the other units as well. The marginal factor cost (MFC) associated with purchasing the extra unit of the good therefore exceeds the going price.

Mathematically, this relationship is represented this way:

$$MFC = P + Q \frac{\partial P}{\partial Q} \tag{1}$$

In the competitive case, $\partial P/\partial Q = 0$ and the marginal expense of hiring one more unit is simply the market price, P. However, if the firm faces a positively sloped supply curve then $\partial P/\partial Q > 0$ and the marginal factor cost exceeds the market price.

A profit-maximizing firm will hire any input up to the point at which its marginal revenue product is just equal to its marginal factor cost. Any departure from such choices will result in lower profits for the firm. Interpreting the demand curve in figure 1 as the marginal revenue product curve of the monopsonist the profit-maximizing equilibrium condition is at point C. The market clearing quantity is at Q_m and the market clearing factor wage rate is taken off the supply curve at point Q_m and is P_m, that is, the buying firm only needs to offer the supplier's MC to have them supply that amount. Price and quantity at P_m and Q_m are lower than the perfectly-competitive outcome P_c and Q_c. The firm has restricted input demand and lowered the factor wage rate by virtue of its monopsonistic position in the market.

The restriction in output from Q_c to Q_m represents the misallocation brought about from the market power. The total value of resources released by this output restriction is shown in figure 1 as the area AEQ_cQ_m. Transferring these inputs elsewhere will cause other goods to be overproduced relative to their Pareto efficient levels. The restriction in output also involves a total loss in producer (supplier) surplus of P_cP_mBE and a loss in purchaser surplus of area CAE. Part of the supplier surplus loss, area P_cP_mAB, is captured by the monopsonist and reflects a transfer of income from suppliers to purchasers. Whether such a transfer is regarded as desirable depends on prevailing societal norms about whether suppliers or the monopsonist are more deserving of such gains. There is no ambiguity, however, about the loss in surplus given by area CBE since this loss is not transferred to anyone. It is a pure "deadweight" loss and represents the principal measure of the allocational harm of the monopsony.

The reduction in price from P_c to P_m also reduces the returns to the investment in producing the input factor. The low return discourages socially optimal investments. Input factor supplies are, therefore, below preferred levels.

In the case of an oligopsony the equilibrium condition will fall between the points B and E on the supply curve. This will produce an output level between the monopsonist level Q_m and the competitive level Q_c. Specific models of oligopsony behavior, such as Cournot and Bertrand, predict precise points on the supply curve where output will occur. Therefore, the welfare loss from an oligopsony structure ranges from that of the pure monopsony down to zero if the outcome is the same as the competitive equilibrium.

Forest Service Response

To overcome the potential problems from market power the Forest Service appraises the stumpage it is preparing to sell to determine the fair market (competitive) price; which becomes the minimum price it will accept for the timber. The appraisal method the Forest Service uses is either a formal appraisal process in which a simplified derived demand or residual value analysis, known as "conversion return" is calculated or a statistical evaluation technique based on stand conditions, past sales, and current market conditions called "transaction evidence"(U.S.D.A. 1984). Once the minimum price is determined the timber is sold through a bidding process where the highest bidder is awarded the rights to the stumpage. All bidders know the minimum bid the Forest Service will accept.

If competition for federal timber is effective then the bidding process rather than Forest Service appraisals will determine fair market prices. In this event, the appraisal system is unnecessary. "In contrast, if the appraisal system is accurate in establishing fair market value, then the problem of effective competition becomes a non-problem. Important public policy issues arise when appraisals are ineffective (appraised values are less than fair market value) and when competition is weak. When these problems coexist, the public does not receive a fair price for its timber" (Mead et al. 1981).

Forest Service Outcome

Historically the appraisal system has not been very effective in establishing the fair market value of stumpage. The most obvious reason is that the end-product selling values and purchaser's costs assumed in the appraisal method and the data for the transaction evidence process are broad averages and reflect the past, not the time when the timber is to be sold or cut.

In the competitive case, bid prices reflect the value of the timber to the purchaser and incorporate his or her expectations of future market conditions. The early 1980s illustrates how poorly the appraisal system works. In 1981 the ratio of bid prices to appraised prices were the highest they have ever been, while in 1982 the ratios were historically low. In 1981 buyers were expecting continued inflation and high demand for timber that would keep values moving upward. In 1982, by contrast, there was a sudden drop in expectations. The appraisal methods do not incorporate current expectations, therefore, they cannot reflect current market value.

An additional complicating factor in using bids to reflect market value is that timber is sold under multi-year contracts with payments, which are adjusted for inflation, not required until the timber is harvested. There are also technical reasons why the formal appraisal process does not reflect fair market value. Examples include: internal adjustments to apportion bids to individual species in multi-species sales and adjustments to costs for road building. Beuter (1985) provides a comprehensive discussion of these issues.

While the transaction evidence method was proposed to overcome some of the problems of the formal appraisal process it brings other problems to the calculations. The most often mentioned is that transactions are not comparable because of differing timber quality, logging and transportation conditions, manufacturing opportunities, market volatility, and site-specific requirements imposed by the Forest Service.

The result of both appraisal methods is a poor estimate of market value without the federal government knowing if they are truly receiving a fair, competitive price for their timber. Thus, there are potential "benefits for the purchaser at the expense of the timber seller, the Federal Government" (Beuter 1985).

MARKET POWER IN WOOD PRODUCTS MARKETS

There is also evidence that the wood products industry exerts market power in output markets. During the 1970s the Federal Trade Commission levied over a half billion dollars in fines on several paper and plywood producers for alleged price-fixing. In 1972 the U.S. Department of Justice required Georgia Pacific to spin off a number of its wood-processing plants into an independent corporation (Louisiana Pacific) because it had too large a market share (Klemperer 1996).

There are a number of ways for firms to have or obtain monopoly or oligopoly power. The primary manner can best be described by the relationship between the average cost curve and the demand curve of the output. The crucial factor in this instance is the size of the minimum efficient scale of production (MES), which is the level of output that minimizes average cost in relation to the size of demand. Therefore, the shape of the average cost curve, which is determined by the underlying technology and costs helps in deciding market structure. If the minimum efficient scale is large relative to the size of the market, we might expect monopolistic conditions to prevail. This is the type of technology that corresponds to relatively large-scale firms that are low cost producers. In wood product markets the pulp and paper industries are the likeliest examples. The extreme situation of this decreasing marginal and average cost over a wide range of output is when the minimum point of the average cost curve falls to the right of the demand curve. These are the circumstances that lead to natural monopolies.

A second reason why a monopoly outcome might occur is that several different firms in an industry might be able to collude and restrict output. This would raise prices and thus increase the firms profits. A third possibility for the formation of a monopoly is purely by historical accident. If one firm is first to enter some market, it may have enough of a cost advantage to be able to discourage other firms from entering the industry.

Another possibility in wood products markets is that the firm is making and selling a product that other firms cannot perfectly reproduce. These firms may have ownership of unique resources such as tree species that possess properties that allow the production of distinctive products. In wood product markets these characteristics may have to do with appearance and/or wood-working ability of the wood products.

In this latter situation other firms may still find it profitable to enter the industry and produce a similar product. The firms will then attempt to differentiate their products from the other. This is referred to as product differentiation and the firms that are most successful will maintain some monopoly power. This type of market power is usually referred to as monopolistic competition since it has elements of both competition and monopoly. It is monopolistic since each firm is facing a downward sloping demand curve for its product and it is competitive since it must compete for customers in terms of both price and the kind of products that it sells. Furthermore, there are no restrictions against new firms entering the markets.

The theoretical derivation that leads to the proposition that prices are higher and output lower under monopoly markets is similar to the monopsony case discussed above (marginal revenue replaces marginal factor cost as the important decision factor). To maximize profits firms equate marginal cost with marginal revenue. Now, however, the firm faces a downward sloping demand curve instead of perfectly elastic one as is the case under perfect competition. This is the analogy of the monopsonist facing the upward sloping supply curve as depicted in figure 1. When demand is downward sloping, marginal revenue is everywhere lower than the demand curve itself (i.e. marginal cost is always higher than the supply curve for the monopsonist). Thus if a monopolist is maximizing profit, marginal revenue and marginal cost are always less than price. The expression for a downward sloping inverse demand function is $P_x(x)$ with $\partial p_x/\partial x < 0$, implying that total revenue is generally a nonlinear function of x: $TR(x)=P_x(x)*x$. Marginal revenue is, therefore, generally not a constant:

$$MR(x) = \frac{\partial TR(x)}{\partial x} = x\frac{\partial P_x}{\partial x} + P_x \tag{2}$$

Equating marginal cost and marginal revenue:

$$MC(x) = MR(x) = x\frac{\partial p_x}{\partial x} + P_x \tag{3}$$

and rearranging:

$$P_x = MC(x) - x\frac{\partial P_x}{\partial x} > MC(x) \qquad since \quad \frac{\partial P_x}{\partial x} < 0 \tag{4}$$

Thus price is greater than both marginal cost and marginal revenue.

The monopolist produces less and charges a higher price than would be the outcome in a competitive market and the welfare loss would be similar to the one discussed under the monopsony/oligopsony discussion. That is, the higher price and lower output would cause a transfer in welfare from the consumers to the monopolist, a transfer of resources from the production of this output to other goods, and a deadweight loss.

LOSS IN ECONOMIC EFFICIENCY FROM MONOPOLY AND MONOPSONY MARKET STRUCTURE

The loss in efficiency from the transfer of resources to the production of other goods, whether from the application of market power in the input or output market, can be easily explained using a general equilibrium perspective. For clarity, the terminology of the monopolist will be utilized, although the monopsony/oligopsony case is similar and obvious.

The lower quantity produced of the good, because of the monopoly, frees up more resources for the production of other goods. This will move the economy to a different point on the production possibilities frontier (PPF). At this new position less of the monopolized good and more of the other goods will be produced. From a general equilibrium perspective, production will still be efficient, however, the resulting distribution of output will not be Pareto optimal. This happens because a monopolist changes the price ratio relative to a general competitive equilibrium price ratio. Assuming that consumers' taste and preferences have not changed and that consumers continue to purchase combinations of goods such that their marginal rates of substitution are equal to

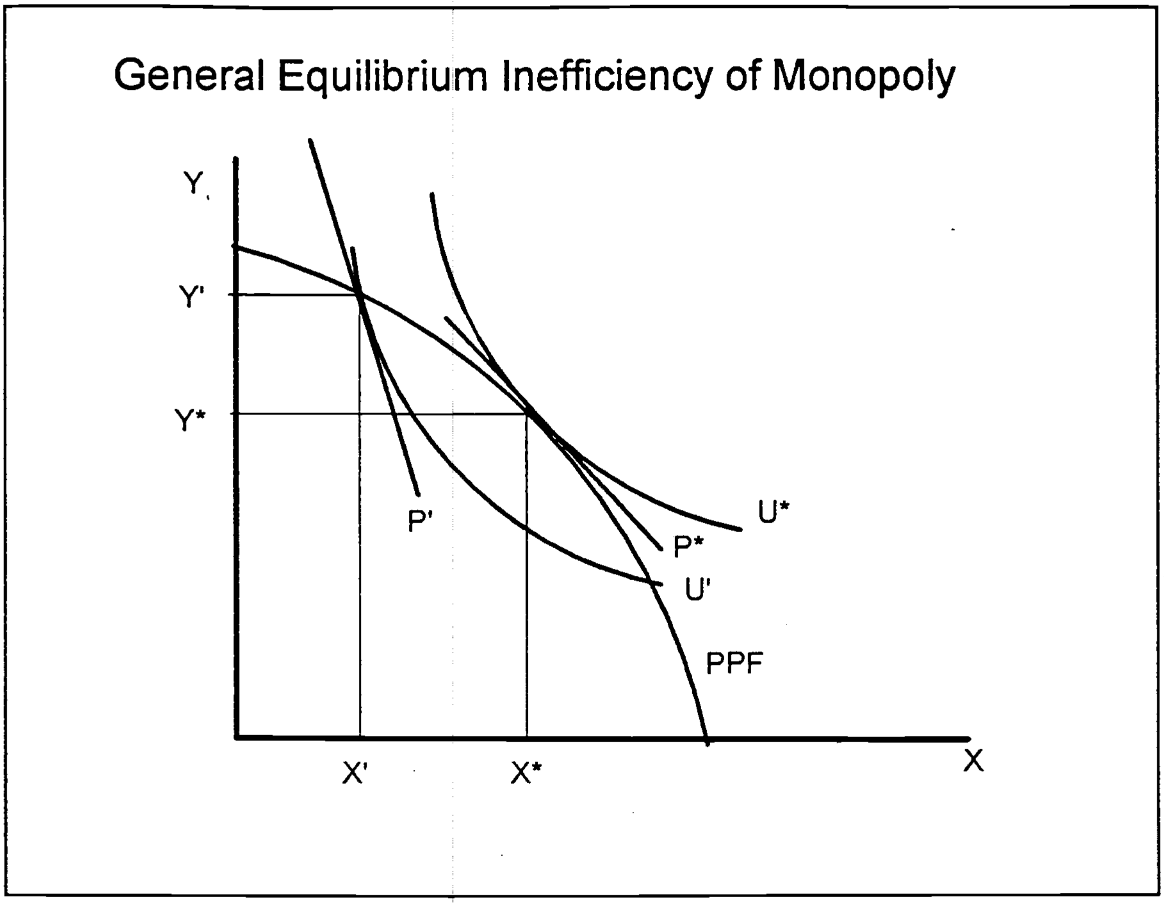

Figure 2 General Equilibrium Inefficiency of Monopoly

the market price ratio, these marginal rates of substitution will no longer be equal to the marginal rate of transformation at the general competitive equilibrium.

Figure 2 clearly shows this phenomenon. In the figure, X^* and Y^* are the production levels of X and Y when both goods are produced competitively. This is the point where the production possibilities frontier and the consumers indifference curves are tangent and the price ratio of the goods is $P_x^* / P_y^* = P^*$. If good X is now produced by the monopolist the price will rise and the quantity will fall. This frees up resources for the production of good Y, which is now relatively less expensive than good X. With the decline in the relative price of Y, the consumer purchases the increased production of Y and the economy moves along the production possibilities frontier. This can be seen at the point X' and Y' in figure 2. The new price ratio has risen to $P_x^M / P_y = P'$. Despite the continued efficiency in production the consumer is no longer able to attain the maximum indifference curve U^*. The consumer still maximizes utility over the budget constraint, implying that his or her marginal rate of substitution is equal to the monopoly price ratio, but the tangency between the indifference curve and the budget line is no longer also a tangency between the indifference curve and the production possibilities frontier. At the monopoly output levels X' and Y' the consumer would always be better off if the output mix would move back in the direction of X^* and Y^*.

OBJECTIVE

The objective of this research is to extend the use of econometric production theory techniques to imperfect markets. First, both primal and dual representations of market power behavior will be presented and secondly, the models will be used to empirically test for the presence of market power in eastern Oregon's lumber and stumpage markets. Additionally, an index for quantifying the degree of market power is presented.

LITERATURE REVIEW

OVERVIEW OF MARKET POWER RESEARCH

Researchers have taken three approaches in the study of market power. The first is the case study where individual industries are examined and informal stories are built from the researchers' unique measures of market power. The second method is the structure-conduct-performance (S-C-P) approach that dates back to the pioneering work of Bain (1959). The approach utilizes Mason's systematic method of studying industries laid out in his famous 1939 article that gave birth to the field of industrial organization (Weiss 1971). The method attempts to relate market characteristics to market performance using the cross-section study of many industries. "This type of analysis postulates implicitly that an industry's structure (for example, industry concentration) determines the conduct of firms (for example, their decisions on output), which in turn determines industry performance" (Carlton and Perloff 1990 p. 360). Performance criteria can include efficiency, equity, macro stability, and progress (Tremblay 1996). The third approach is clearly different from the first two and ". . . is motivated by a concern that it is not easy to calculate measures of performance and that they must be estimated differently than is usually done in structure-conduct-performance studies" (Carlton and Perloff 1990 p.361). This approach, called the "new empirical industrial organization" (NEIO) uses theoretical results of profit maximizing behavior to econometrically estimate the amount by which industry behavior deviates from competition. Bresnahan (1989 p. 1012) summarizes the new approach as having four central ideas:

- Firms' price-cost margins are not taken to be observables; economic marginal cost (MC) cannot be directly or straightforwardly observed. The analyst infers MC from firm behavior, uses differences between closely related markets to trace the effects of changes in MC, or comes to a quantification of market power without measuring cost at all.

- Individual industries are taken to have important idiosyncracies. It is likely that institutional detail at the industry level will affect firms' conduct, and even more likely that it will affect the analyst's measurement strategy. Thus, practitioners in this literature are skeptical of using the comparative statics of variations across industries or markets as revealing anything, except when the markets are closely related.

- Firm and industry conduct are viewed as unknown parameters to be estimated. The behavioral equations by which firms set price and quantity will be estimated, and parameters of those equations can be directly linked to analytical notions of firm and industry conduct.

- As a result, the nature of the inference of market power is made clear, since the set of alternative hypotheses which are considered is explicit. The alternative hypothesis of no strategic interaction, typically a perfectly competitive hypothesis, is clearly articulated and is one of the alternatives among which the data can choose.

FOREST PRODUCTS LITERATURE

The market structure research in the field of forestry and wood products follows all three paradigms. Ireland (1976), using the S-C-P paradigm, examined the timber-based industries in the United States and looked at market concentration--the degree to which dominant firms control an industry's output. Ireland estimated both the four and eight firm concentration ratio, the most common measure of concentration. He found the eight firm ratio to be below 23 percent for the lumber sector in the early 1970s. This is in the lower one-eighth of the four-digit SIC manufacturing industries in the U.S. The ratio in the Pacific Northwest, at 34 percent, was in the moderately concentrated category.

For the other sectors Ireland found varying ratios. The U.S. and the northwest's plywood industries were found to be in the concentrated category while the level of concentration in the paper industries varied by product type and geographical location.

By the 1980s the national percentages hadn't changed appreciably (figure 3). Twenty-five per cent of the value of all wood products shipments of all companies in the U. S. was accounted for by the 4 largest companies. In the structural panels and the pulp industries, the 4 largest companies accounted for 41 and 45 per cent, respectively. The 4 largest companies in the lumber industry accounted for 16 per cent of the value of shipments and the 4 largest firms of the other primary timber products industries

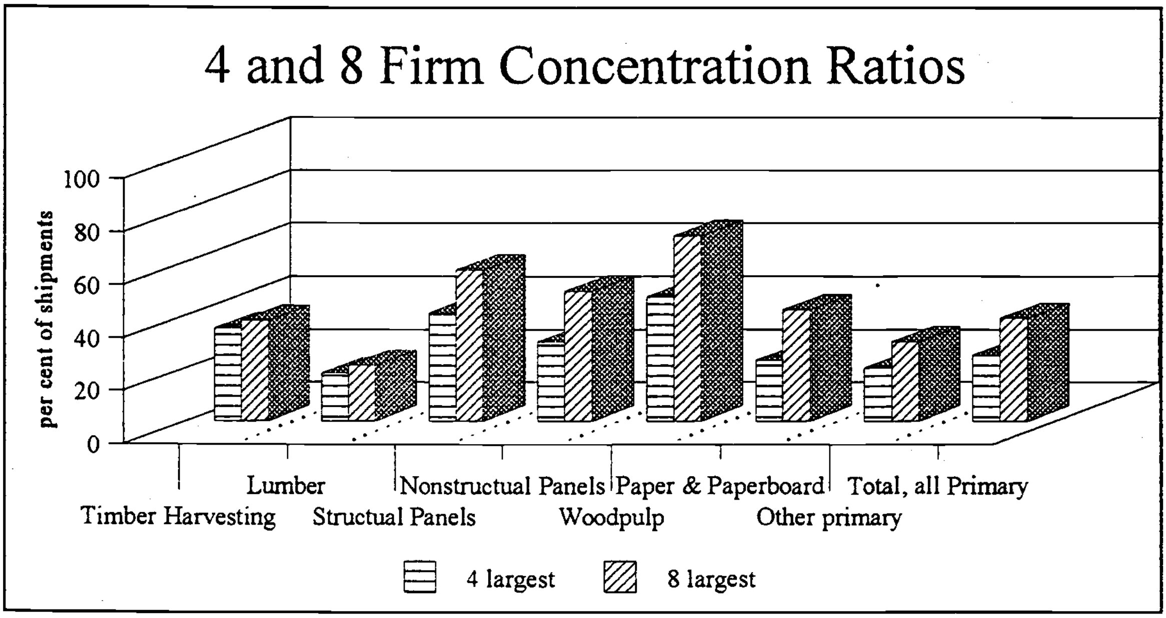

Figure 3. 4 and 8 firm concentration ratios

accounted for 20 per cent of the value of shipments.

Mead (1966), using the case study approach and data from the late 1950s and early 1960s, found that wood products firms in the Douglas-fir region were competitive as sellers of lumber but had oligopsony power as buyers of National Forest timber. Using bid-appraisal ratios the analysis found that competition varied with number of bidders and inversely with the percentage of total volume purchased by large firms, and inversely with sale size. His analysis also rejected the hypothesis that sealed bids would produce higher prices than oral bids. When he revisited the study in the 1970s, however, he found that competition for National Forest timber had increased (Mead et al. 1981).

Haynes (1979, 1980a, and 1980b) used overbid (the amount the purchase price is over the minimum bid the Forest Service would except for the timber) as the measure of classifying whether a timber sale was competitive or noncompetitive. This measure was used because it provides a cardinal measure of competition, unlike the bid appraisal ratios which provide only an ordinal measure. The ordinal measure is only relative to other sales observed at the same time. This can be important if differential rates of inflation are recognized in the cost and price elements leading to the appraised price and in the premium that bidders are willing to pay for the timber.

Haynes defined a timber sale as noncompetitive if the overbid was less than one-half of one percent of the average overbid for the geographical area of interest. He then classified an area as competitive or noncompetitive depending on the percent of sales in the area that were competitive. Haynes found that overbid varied directly with potential profitability of the timber sale and that in areas classified as noncompetitive, sealed bidding in general increased overbids.

Although Haynes classified some regions as noncompetitive, he did not find indications that there was collusive activity. As stated above, most noncompetitive sales were found to be noncompetitive because they appeared to the bidders to have a low potential for profitability.

The only work to date that applies some of the newer techniques embodied in the NEIO framework to the forestry sector is that done by Murray (1992) and Bergman and Brännlund (in press). Murray's research uses a spatial model of industry location to explain market power and applies it to the US pulpwood and sawlog markets. The results find that pulpwood markets are more oligopsonistic than sawlog markets but both perform closer to perfect competition than to monopsony. The only real short coming of the work is the use of national level data. Timber markets exhibit regional heterogeneity, therefore his results, that are averages for the whole nation, tell nothing about individual regions. Bergman and Brännlund apply the method to the Swedish pulpwood market and obtained results that lead them to believe that the market is "consistent with a situation in which an unstable cartel is able, during some periods, to restrict competition and during others not"(p. 13). Both these models will be discussed in more detail below, under the heading **THEORETICAL MODELS**.

PROPOSED RESEARCH

The research proposed here will follow the third or NEIO paradigm. A detailed overview of the approach will be undertaken first, followed by the development of the theoretical underpinnings of the decision-making process of a firm that has market power in both the input and output markets. The aggregation assumptions necessary to convert the firm-level model into an industry model is developed next. Finally, both primal and dual representations of the model are presented and empirically applied to eastern Oregon's lumber and stumpage markets.

REVIEW OF THE NEIO APPROACH

Bresnahan (1989) presents a thorough review of the NEIO literature up to 1988. Most of what follows is taken from there.

Quantity and price setting in oligopoly is the area where most of the published work is centered. The primary subtopics covered are those common to many studies of market power and include the formation and enforcement of collusive agreements, the extent of single-firm market power under product differentiation, the magnitude and determinants of firm and industry price-cost margins, and the nature of noncooperative oligopoly interactions.

The advances that the NEIO framework brings to the measurement of market power can be seen in a simple econometric model of oligopoly behavior in a single, homogeneous-product industry. Begin with an inverse demand function:

$$P_t = D(\underset{\sim}{Q}_t, Y_t, \delta, \epsilon_{dt}) \tag{5}$$

where Y_t are all the known demand shifting variables and δ are the unknown parameters of the demand function. The equation error terms ϵ_{dt} are written so that they may enter in a nonlinear manner.

The total cost function in the stylized model is:

$$C_{it} = C(Q_{it}, W_{it}, Z_{it}, \Gamma, \epsilon_{cit}) \tag{6}$$

W_{it} is the vector of factor prices paid by firm *I* at time or observation *t*, Z_{it} are other variables that shift cost, Γ are the unknown parameters, and ϵ_{cit} are the error terms. There are *I* subscripts on Z and W because some of the applications use the comparative statics of equilibrium of costs of individual firms. The definition of marginal cost follows directly from **(6)**:

$$MC = \frac{\partial C}{\partial Q} = C_1(Q_{it}, W_{it}, Z_{it}, \Gamma, \epsilon_{cit}) \tag{7}$$

where the nonlinearity of cost in the error term has been exploited.

Outside the perfectly competitive model, firms do not have traditional supply curves. Instead, price- or quantity-setting behavior follows the more general supply relations:

$$P_t = C_1(Q_{it}, W_{it}, Z_{it}, \Gamma, \epsilon_{cit}) - D_1(Q_t, Y_t, \delta, \epsilon_{dt}) Q_{it} \theta_{it} \tag{8}$$

where D_1 is the derivative of the inverse demand function. Since $P + D_1 Q$ is monopoly marginal revenue (see introductory chapter), equation **(8)** has the interpretation that MC = "perceived" MR for oligopoly models. The parameters θ index the competitiveness of oligopoly conduct on a scale of zero to one. As θ_{it} moves farther from zero, the conduct of firm *I* moves farther from that of a perfect competitor. When θ_{it} equals one we have a monopolist.

Some of the empirical studies estimate equations (6) and (8) directly as structural equations while others that lack data on price or quantity use a reduced form model. Other work that lacks firm-specific quantity data use aggregate data.

There are three advantages to this kind of modeling. The first is that the econometric approach is structural, so that each parameter has an economic interpretation. Substantial departures of the estimated parameters from expected values can help decipher difficulties with or shortcomings of the analysis. The second advantage is, if the interpretation of θ is correct, the relationship of the estimates of conduct to theory are clear. The other advantage is that given the structural nature of the econometrics the reason why the data identify the conduct parameters is clear.

The form in which the nonprice taking conduct parameter θ is modeled is central to the inferences made about market power from any particular study. One group of analyses takes the specification of θ directly from a theory or group of theories while another group of studies use a looser interpretation of θ. In the latter papers, θ is used to estimate "oligopoly conjectural variations," that is, a firm's "expectations" about how other firms will react to an increase in their output.

In the first set of papers the method associates a different specific value of the parameter θ depending on the particular model of strategic behavior being estimated. The second approach allows θ to be a continuous-valued parameter. The continuous-valued θ method uses θ to describe firms' conjectural variations.

Though there has been some criticism of the conjectural variation approach it is misplaced and has to do with the difference in the theoretical definition of conjectural variation and the empirical definition. The "distinction . . . is between (i) what firms believe will happen if they deviate from the tacitly collusive arrangements and (ii) what firms do as a result of those expectations" (Bresnahan 1989 p. 1029). In the empirical analysis it is the second that is being estimated. "Thus, the estimated parameter reveals price- and quantity-setting behavior; if the estimated 'conjectures' are constant over time, and if breakdowns in the collusive arrangement are infrequent, we can safely interpret the parameters as measuring the average collusiveness of conduct. The 'conjectures' do not tell us what will happen if a firm autonomously increases output (and thereby departs from the cartel agreement), the normal sense in which theoretical papers would use 'conjectural variations'" (Bresnahan 1989 p. 1029).

THEORETICAL MODELS

The method proposed for this research falls in the "conjectural variations" category of the current research. The theoretical model that will be estimated comes from the work of Chang and Tremblay (1991), Azzam and Pagoulatos (1990), Schroeter (1988), Appelbaum (1979 and 1982), Murray (1992), and Bergman and Brännlund (in press).

The first six analyses develop a firm index of market power that measures the extent to which an input and/or an output price actually paid and/or received by a firm deviates from the value of the factor's marginal product and/or product's marginal cost. From the firm measure an index of aggregate market power for the industry is derived. Bergman and Brännlund forego the index and only test for the existence of market power.

The first three models and the last two extend the oligopoly work of Appelbaum to include oligopsony; allowing firms to possess market power in the input market, the output market, or both markets. Because of the dearth of firm-level data, Appelbaum, Schroeter, Azzam and Pagoulatos, Murray, and Bergman and Brännlund extend their firm-level theoretical models to industry models by describing the necessary aggregation assumptions required for consistency before empirically applying them. Chang and Tremblay propose an industry model by using the results of individual firm estimations.

The theoretical and applied models developed for this research are based on these models. It expands on all of them by including both primal and dual representations that allow for the existence of market power in the input and output markets simultaneously and/or by using a more efficient simultaneous estimation process.

The first primal model discussed follows the work of Chang and Tremblay while the second is a modification of Azzam and Pagoulatos'. The dual model follows the works of Murray and Bergman and Brännlund, but explicitly identifies the role of the shadow prices of both the output and input. Murray and Bergman and Brännlund only examine the input markets. The dual model is based on a behavioral or shadow profit function.

MODEL DEVELOPMENT

To begin consider an industry with N firms producing a homogeneous product. The inverse demand function for the final product of the firm is:

$$p = p(Q) \tag{9}$$

where $Q = \sum q_i$ is industry output and q_i is the output of the ith firm. It is assumed N is small and entry is somehow limited to allow for non-competitive behavior.

On the production side assume the i^{th} firm uses one material factor of production--the factor of interest (stumpage), x_{1i}, and M-1 non-material inputs, x_{ji} (j=2..M). The non-material factors of production are assumed to be purchased in competitive markets.

Input market sellers are also assumed to have no market power. In our example we assume when public agencies control a large percentage of the stumpage in a region their institutional framework is designed to mimic the marginal cost pricing of a competitive market (see the introductory chapter).

The inverse market supply of the material factor of production is given by

$$w_1 = W_1(X_1) \tag{10}$$

where, X_1 is total supply of the material factor of production and w_1 is the per unit price of X_1. Also dW_1/dX_1 is assumed greater than zero. Finally, the ith firm's production function is

$$q_i = f_i(x_{ij}) \qquad j=1,...,M \tag{11}$$

and is assumed to be concave and continuously twice differentiable.

The problem for the ith firm is to choose the amount of the material input, x_{i1}, and the amounts of the non-material inputs, x_{ij} (j=2,...,M) in order to maximize the firm's profits:

$$Max \ \ \Pi_i = p(Q)q_i - W_1(X_1)x_{1i} - \sum_{j=2}^{M} w_j x_{ji} \tag{12}$$

where Π_i is the ith firm's profits and w_j are the prices of the non-material inputs. The first-order necessary conditions are:

$$(\frac{dp}{dQ})(\frac{dQ}{dq_i})(\frac{\partial q_i}{\partial x_{1i}})q_i + p(\frac{\partial q_i}{\partial x_{1i}}) - (\frac{dW_1}{dX_1})(\frac{dX_1}{dx_{1i}})x_{1i} - w_1 = 0 \tag{13}$$

and

$$(\frac{dp}{dQ})(\frac{dQ}{dq_i})(\frac{\partial q_i}{\partial x_{ji}})q_i + p(\frac{\partial q_i}{\partial w_{ji}}) - w_j = 0 \qquad j=2,...,M \tag{14}$$

The optimality conditions in equations **(13)** and **(14)** say that a firm equates it *perceived* marginal resource cost with its *perceived* marginal revenue product. It is *perceived* since the firm must conjecture how its input and output choices affects total industry input and output ($\partial X_1/\partial x_{1i}$ and $\partial Q/\partial q_i$). If the market were perfectly competitive the firms would think they had no appreciable affect on the market and $\partial X_1/\partial x_{1i}$ and $\partial Q/\partial q_i$ would equal zero. In this case w_i would equal the value of the marginal product (the well-known first-order condition for profit maximization).

A quick and easy way to identify the presence of market power would be to interpret the partial derivatives in equation **(13)** as estimatable coefficients of the parameters q_i, p, and x_{1i} and statistically estimate:

$$w_1 = \tau_1 p + \tau_2 q_i - \tau_3 x_{1i} \tag{15}$$

Significant positive values of τ_2 and τ_3 in this market power identifying equation would indicate the presence of oligopoly and oligopsony power, respectively. The estimation alone, however, would not reveal the degree of market power.

SHADOW PRICE OF INPUT AND OUTPUT

Equations **(13)** and **(14)** can be rearranged:

$$p\frac{\partial q_i}{\partial x_{1i}}[1-\frac{\alpha_i}{\eta}] - w_1[1+\frac{\beta_i}{\epsilon}] = 0 \tag{16}$$

$$p\frac{\partial q_i}{\partial x_{ji}}(1-\frac{\alpha_i}{\eta})-w_j = 0 \qquad j=2,...,M \tag{17}$$

where

MPx_{1i} $= (\partial q_i/\partial x_{1i})$ -- the marginal product of the material factor of production of the ith firm,

η $\equiv -(dQ/dp)(p/Q)$ -- the price elasticity of demand in the output market,

α_i $\equiv (dQ/dq_i)(q_i/Q)$ -- the ith firm's output conjectural (or perceived) elasticity with respect to total industry output.

ϵ $\equiv (dX_1/dw_1)(w_1/X_1)$ -- the input price elasticity of market supply for the material factor,

β_i $\equiv (dX_1/dx_{1i})(x_{1i}/X_1)$ -- the ith firm's input conjectural elasticity with respect to the industry's total material factor demand.

Rearranging equation **(16)** further equates the perceived marginal revenue with the perceived marginal cost:

$$p(1-\frac{\alpha_i}{\eta})\frac{\partial q_i}{\partial x_{1i}} = w_1(1+\frac{\beta_i}{\epsilon}) \qquad \textbf{(18)}$$

Therefore, the shadow prices of the output and input are $P(1-\frac{\alpha_i}{\eta})$ and $w_1(1+\frac{\beta_i}{\epsilon})$, respectively.

If both markets were competitive the value of the marginal product would equal the price of the input since α_i and β_i would equal zero. Now, however, the firm will behave by maximizing profits against the perceived prices and costs. The firm's shadow or behavioral profit function becomes:

$$\Pi^s = p(1-\frac{\alpha_i}{\eta})q_i(x_{1i}) - w_1(1+\frac{\beta_i}{\epsilon}) - \sum_{j=2}^{M} w_j x_{ji} \qquad \textbf{(19)}$$

Later this shadow profit function will be used in the dual model to derive optimal output and input relationships that will be empirically estimated to produce estimates of β_i and α_i.

SPECFIC MODELS OF MARKET POWER

As mentioned above if there were only one firm in the market (monopoly and monopsony) then the conjectual elasticities would equal 1. For Cournot behavior the conjectual elasticites would be equal to the firm's shares of total industry input and/or output. For Bertrand behavior the elasticites would equal zero (Table 1). The Cournot[2] model is based on the assumption that each firm decides on its output level with the assumption that other firms output is fixed. Bertrand[3] believes that firms commit themselves to prices (not output, as Cournot states) and then adjust their rates of production to fit consumer demand at those prices. The outcome of this type of behavior leads to price equalling marginal cost in the output market and cost of the input equalling value of the marginal product in the input market.

Table 1. Specific models of market power.

Elasticity	Bertrand	Cournot	Monopoly	Monopsony
α_i	0	q_i/Q	1	-
β_i	0	x_i/X	-	1

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[2]Agustine Cournot (1801-1877), *Researches Into the Mathematical Principles of the Theory of Wealth* (in French, 1838), trans. N. T. Bacon (Homeood, Il: Irwin, 1963).

[3]This review can be found in French in Journal des Savants, Sep. 1883.

INDEX OF MARKET POWER

An index of the degree of market power is the difference between the value of the marginal product and the input price all divided by the value of the marginal product:

$$I_i = [p(MPx_{1i}) - w_1] / [p(MPx_{1i})] \tag{20}$$

using equation 4-9 this equals

$$I_i = \left(\frac{\beta_i}{\epsilon} + \frac{\alpha_i}{\eta}\right) / \left(1 + \frac{\beta_i}{\epsilon}\right) \tag{21}$$

Because the value of the marginal product must be greater than or equal to w_1, which is greater than zero, the value of I_i ranges from 0 to 1. When the factor is paid equal to the value of its marginal product, $p(MPx_{1i})=w_1$, $I_i = 0$ and the markets are allocated efficiently; as the difference in the value of the marginal product and the factor price increases, I_i approaches 1. Thus, greater inefficiency is implied by higher values of I_i.

Because this index allows for non-competitive behavior in both the factor and output markets, Chang and Tremblay refer to it as an oligopsony/oligopoly index. It directly reflects the allocative inefficiency due to market power by measuring the non-competitive rents acquired by the firm as a proportion of the value of the marginal product.

α_i/η reflects the non-competitive performance in the output market and reduces to the well known Lerner Index of $1/\eta$ for the case of the pure monopolist. β_i/ϵ reflects the non-competitive performance in the input market as identified by Schroeter. It reduces to $1/\epsilon$ for the pure monopsonist.

The index is quite general since no restrictions are placed on the conjectural elasticities of the firm. In the case of Cournot behavior in both the input and the output market ($dX/dx_{1i}=1$ and $dQ/dq_i=1$), β_i becomes the input market share and α_i the output market share of the *i*th firm.

If it is assumed the output market is competitive and the input market is oligopsonistic, as is the more likely possibility than the other way around in lumber and stumpage markets, $\alpha_i=0$ (because $dQ/dq_i=0$) and $0<\beta_i<1$, the firm index reduces to

$$I_i = \frac{\beta_i}{(\epsilon+\beta_i)} \tag{22}$$

FIRM AGGREGATION

Given the necessary data it would not be difficult to estimate this theoretical model. However, it is not usually easy to obtain the required firm-level cross-section, time-series data. The common alternative that is employed for this research will be to look at the problem at the industry or aggregate level.

To do this, however, requires an assumption on the behavior of the firms in equilibrium. This assumption is that the conjectural elasticities are invariant across firms. Appelbaum (1982) shows how this assumption holds in equilibrium of an oligopolistic market by the theory of linear aggregation of cost functions. Linear aggregation consistency, however, constrains the analyses to cost functions of the Gorman-Polar form and production functions that are quasi-homothetic (and identical in equilibrium). Azzam and Pagoulatos extend the assumption of invariant conjectural elasticities to the input market. While this assumption can also be shown to hold in equilibrium if one wishes to satisfy linear aggregation of production, it restricts the estimatable production technology even further. Therefore, it is left as an assumption. Appendix A derives the equilibrium aggregation assumptions and their constraining results.

Employing the assumption of invariance of conjectural elasticities across firms allows the subscript *i* on both conjectural elasticities β_i and α_i to be dropped.

EMPIRICAL MODELS

PRIMAL AND DUAL REPRESENTATIONS

A brief discussion of the primal and dual representation is warranted at this time. The heart of production economics is the determination by the firm of the optimal combination of resources to produce the profit maximizing level of output given the technical and economic circumstances.

The traditional, neoclassical approach to modeling this behavior is to use the primal method. The primal approach begins with the direct representation of the production process of the firm and the assumption of profit maximizing behavior. Optimal product supply and factor demand equations consistent with this optimizing behavior are then obtained by solving the first-order conditions. Refutable hypotheses and comparative static results can then be empirically tested with real data.

The dual approach is economically equivalent to the primal method and allows one to obtain product supply and factor demand equations simply by the partial differentiation of an indirect profit or cost function. These are Hotelling's and Shepard's lemmas.

While not offering any profound insights into production economic theory the dual approach is quite useful because it can be a more convenient way to obtain the supply and demand equations than the primal method; where it is at times impossible to analytically obtain them (Pope 1982).

Each method, however, usually requires both prices and quantities so that data requirements for empirical estimation are similar. Both methods, also, can be used to test structural issues such as returns to scale, homotheticity, separability, structural change, homogeneity, etc.

Two primal and one dual approach will be outlined here. The empirical estimation will use the dual model and one of the primal representations.

PRIMAL MODELS

The primal models are based on the estimation of the production, output market demand, input market supply, and optimality functions discussed above. In aggregate form they are:

$$Q^P = f(X, Z_1) \tag{23}$$

$$Q^D = g(P, Z_2) \tag{24}$$

$$W = h(X_T, Z_3) \tag{25}$$

$$P\frac{\partial Q^P}{\partial X}\left(1 - \frac{\alpha}{\eta}\right) = W\left(1 + \frac{\beta}{\epsilon}\right) \tag{26}$$

Here X is the input of interest used in the production of Q. X_T is the total amount of input supplied from the region, and Z_1, Z_2, and Z_3 are vectors of relevant exogenous variables.

The first primal method is presented since it is the direct estimation of the above equations and clearly describes the economic behavior that is being modeled. The estimation procedure is a two-step econometric procedure proposed by Chang and Tremblay. In the first step the first three equations are simultaneously estimated to produce estimates of the marginal product of input X_l, $(\partial Q/\partial X_l)$, the slope of the inverse demand function in the output market (∂P/∂Q), and the slope of the inverse supply function in the factor market ($\partial W/\partial X_1$). The second step uses the results of the first step to estimate the following rearranged version of the optimality condition (the market power identifying equation in all its parts):

$$w = \theta_1[p(\frac{\partial Q}{\partial X})] + \theta_2[\frac{\partial P}{\partial Q}\frac{\partial Q}{\partial X}Q] - \theta_3[\frac{\partial w}{\partial X}X] \tag{27}$$

Here θ_1, θ_2, and θ_3 ($\theta_2 \equiv dQ/dq$ and $\theta_3 \equiv dX/dx$) are the unknown parameters and used to determine if oligopsony and oligopoly price distortions exist. Significant values of θ_2 and θ_3 indicate the presence of oligopoly and oligopsony, respectively. The degree of market power can be calculated by inserting the estimates for η and ϵ from the demand and inverse supply functions and α, and β into the index equation.

Two-step econometric procedures like this have been shown to produce consistent estimates of the parameters. The standard errors reported for the second step, however, are biased downward unless information on the variances of the estimated coefficients calculated in the first step are utilized (Murphy and Topel 1985).

The reason this model is not estimated is that it requires a linear demand curve so that the slope of the curve at the equilibrium prices and quantities does not change over time. If the slope changes over time it would be impossible to separate out the effects of prices and quantities in the model. The perfect multicollinearity that would result would keep the model from providing estimates (Appendix B shows this).

The second primal model, which will be utilized, follows directly from the preceding model and contains a slight modification of the method used by Azzam and Pagoulatos. The modification from both the above model and Azzam and Pagoulatos' is that the whole model is simultaneously estimated, producing more efficient parameter estimates. The method incorporates the optimality conditions into the inputs' cost shares (cost of each input in relation to total revenue). This allows the whole model (the share equations, the production function, the output demand function, and the inverse input supply function) to be estimated simultaneously. Azzam and Pagoulatos used exogenously estimated elasticities in their model. In relation to the model presented above, however, there is a cost, and that is the need for price information on the other inputs used in the production process.

The share equations, which incorporate the optimality conditions are:

$$S_{X}' = \frac{W'X'}{PQ} = (*)(1-\frac{\alpha}{\eta})$$

$$S_{X_1} = \frac{W_1X_1}{PQ} = (*)[\frac{1-\frac{\alpha}{\eta}}{1+\frac{B}{\epsilon}}] \qquad (28)$$

where (*) is a function that depends on the functional form of the production function (the derivation of these equations will be shown in the chapter on functional forms.

X_1 is the input of interest and X' are the other inputs. The estimation of these equations with the production function, the output demand equation, and the inverse supply equation will produce estimates for η, ϵ, α, and β. The production function is needed in the estimation to complete the identification of the model structure.

DUAL MODEL

The dual approach uses an indirect shadow profit function. Denoting the function π^S and applying Hotelling's lemma (using the shadow price instead of the actual price) gives the optimal output and input levels. It is appropriate to use the shadow prices with Hotelling's lemma if the conjectures of the firms are based on exogenously occurring factors (Kerkvliet 1995). Within the framework described here the primary factor that allows for the presence of market power is the number of firms, which is an exogenous factor for each firm.

The shadow profit function and the optimal input and output functions are:

$$\Pi^s = P\varrho_p * Q(P\varrho_p, W_1\varrho_w, W') - W_1\varrho_w * X_1(P\varrho_p, W_1\varrho_w, W') - W' * X'(P\varrho_p, W_1\varrho_w, W')$$

$$\frac{\partial \Pi^s}{\partial P\varrho_p} = \frac{1}{\varrho_p}\frac{\partial \Pi^s}{\partial P} = Q(P\varrho_p, W_1\varrho_w, W')$$

$$-\frac{\partial \Pi^s}{\partial W_1\varrho_w} = -\frac{1}{\varrho_w}\frac{\partial \Pi^s}{\partial W_1} = X_1(P\varrho_p, W_1\varrho_w, W') \qquad \textbf{(29)}$$

$$-\frac{\partial \Pi^s}{\partial W'} = X'(P\varrho_p, W_1\varrho_w, W')$$

where, $\varrho_P = (1 - \frac{\alpha}{\eta})$ and $\varrho_W = (1 + \frac{\beta}{\epsilon})$.

To produce efficient estimates this model is estimated using the optimal output and input functions simultaneously with the output demand and inverse input supply functions.

EMPIRICAL ANALYSIS

AREA OF ANALYSIS

Eastern Oregon (figure 3) was chosen as the area of analysis for a number of reasons; the Forest Service is the major supplier in the region and is preparing a program to restore ecosystem health to the region that will likely include plans to increase timber harvest levels to rid the forests of dead and dying, insect-infested trees. The region is also almost exclusively self-contained in terms of log flow--over 92 per cent of the logs used by the lumber industry comes from within the region's borders and virtually no timber is exported. There are also only 20 operating lumber mills and two operating veneer mills in the region (Ward 1995).

Over 70 per cent of the forest land available for timber harvest in the region is in public ownership and over half the harvest has come from these lands (Sessions 1990). The majority of the public ownership harvests have come from Forest Service sales (Howard 1989).

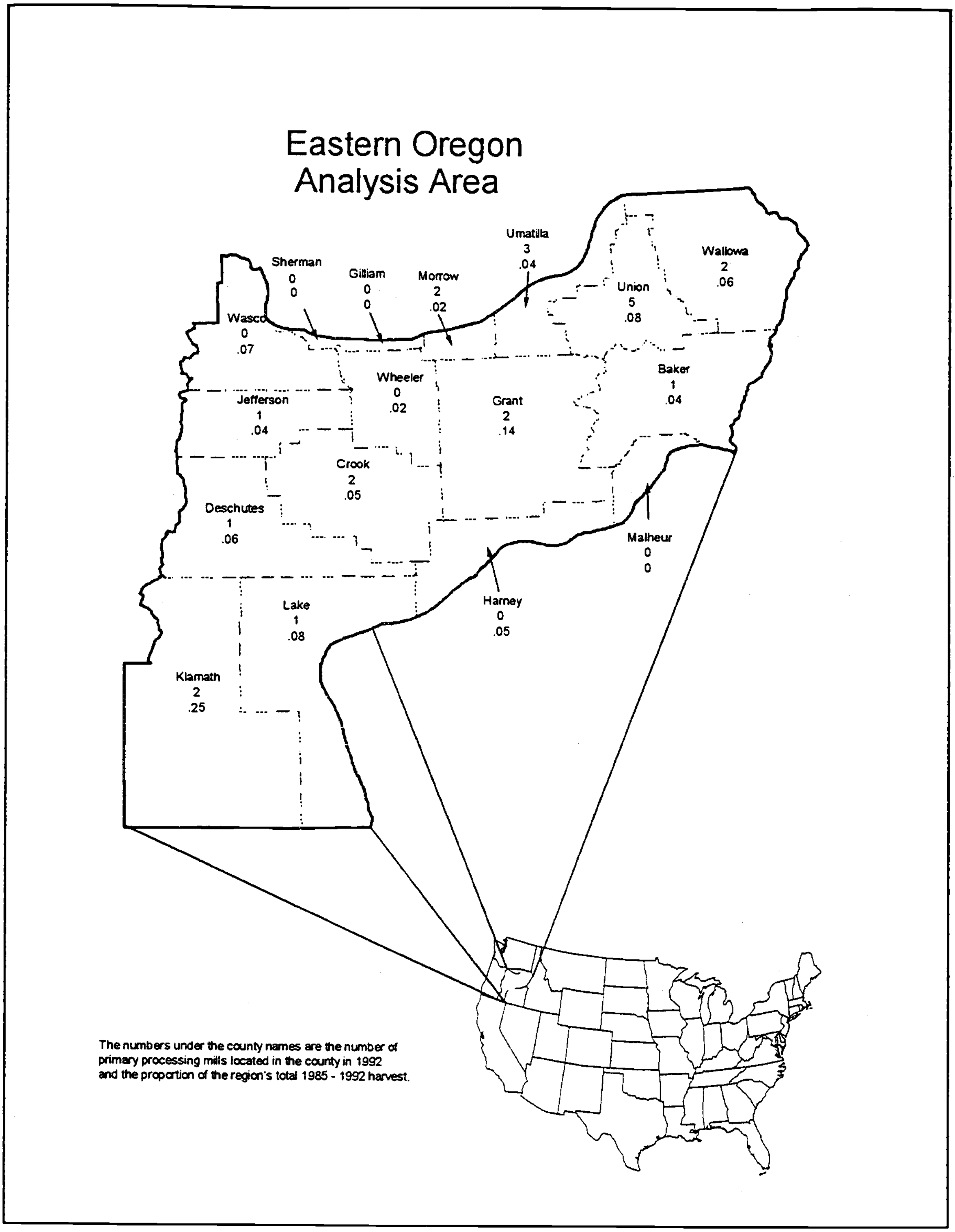

Figure 4 Area of Analysis

FUNCTIONAL FORMS OF EQUATIONS TO BE ESTIMATED

The functional forms of the equations that are needed in the analysis will now be described. Since the output demand and inverse input supply functions are used for both models they will be discussed first, followed by the specific equations for the primal and dual models.

Input Supply Function

Total stumpage supply is assumed to be a function of stumpage price and shifts in public stumpage sold and privately-owned growing stock (Merrifield and Haynes 1983). The amount of timber sold from National Forests and other public agencies are assumed to be established by agency policy, while the supply of stumpage from private landowners is assumed to be responsive to the level of existing inventories and to current stumpage prices. The inverse stumpage supply function is:

$$W_1 = h(X_1, GS, PUB_{sold}) \tag{30}$$

where, X_1 is stumpage quantity harvested, W_1 is stumpage price, GS is forest industry and nonindustrial private forest landowner growing stock, and PUB_{sold} is stumpage sold from public lands.

The functional form of the inverse stumpage supply is conventional. It is one exhibiting constant elasticity. A constant elasticity form is needed for both the supply and demand equations so that the model is identified. The log-linear form of the function is:

$$lnW_1 = \gamma_0 + \gamma_{X_1} lnX_1 + \gamma_{GS} \ln GS + \gamma_{PUB_{sold}} lnPUB_{sold} \tag{31}$$

where γ_{X_1} is the inverse of the supply elasticity, ϵ.

The expected signs of the coefficients are straight forward. It is assumed that as price increases more stumpage will be supplied to market, therefore, the coefficient on total supply is positive. The signs of the private inventory and public stumpage sold variables are hypothesized to be negative; as these increase, stumpage price falls.

Output Demand Function

In general the quantity demanded of softwood forest products is related to its own price, the price of substitutes, and measures of construction activity (Merrifield and Haynes 1983). A major substitute for the produced product is interior British Columbia (BC) lumber, therefore, the per unit value of softwood lumber imports from BC is an appropriate substitute price. Expenditures on private construction of U.S. residential buildings is a commonly used measure of construction activity. The expected signs of these variables are also self-evident. As price of lumber rises less will be demanded, thus a negative coefficient on price. Alternatively, as the price of the substitute rises more lumber from the region will be demanded and as construction expenditures increase lumber demand should also increase.

A constant elasticity function is also employed for the output demand function. The log-linear form of the equation is:

$$lnQ^{D} = \zeta_0 + \zeta_Q lnP + \zeta_{PC} lnP_C + \zeta_{CON} lnCON \tag{32}$$

where P is price of Pacific Northwest east side lumber, Q^D is the quantity, P_C is import lumber price, and CON is the measure of construction activity. Here ζ_Q is the elasticity of demand, η.

Production Function

The final equation in the primal model is the specification of the production technology. Initially the flexible translog production function was planned on being utilized (Chambers 1988). It was chosen since it is a generalization of the Cobb-Douglas and CES production functions and has the desirable characteristic that it doesn't impose severe *a priori* constraints on the production characteristics of the industry. The three-input translog production function is:

$$\begin{aligned} lnQ = {} & \gamma_0 + \gamma_L lnL + \gamma_S lnS + \gamma_K lnK \\ & + 1/2[\gamma_{LL}(lnL)^2 + \gamma_{LS} lnL\ lnS + \gamma_{LK} lnL\ lnK + \gamma_{SL} lnS\ lnL \\ & + \gamma_{SS}(lnS)^2 + \gamma_{SK} lnS\ lnK + \gamma_{KL} lnK\ lnL + \gamma_{KS} lnK\ lnS \\ & + \gamma_{KK}(lnK)^2] \end{aligned} \tag{33}$$

The marginal products for the three inputs are (since $\frac{\partial Q}{\partial X} = \frac{\partial lnQ}{\partial lnX}\frac{Q}{X}$ see appendix B):

$$\frac{\partial Q}{\partial L} = (\gamma_L + \gamma_{LL} lnL + \gamma_{LS} lnS + \gamma_{LK} lnK)(\frac{Q}{L})$$

$$\frac{\partial Q}{\partial S} = (\gamma_S + \gamma_{SL} lnL + \gamma_{SS} lnS + \gamma_{SK} lnK)(\frac{Q}{S}) \tag{34}$$

$$\frac{\partial Q}{\partial K} = (\gamma_K + \gamma_{KL} lnL + \gamma_{KS} lnS + \gamma_{KK} lnK)(\frac{Q}{K})$$

Given these equations and the aggregate optimality conditions of equations 16 and 17 the share equations become:

$$S_S = \frac{w_S S}{PQ} = (\gamma_S + \gamma_{SL} lnL + \gamma_{SS} LnS + \gamma_{SK} lnK) \left(\frac{1-\frac{\alpha}{\eta}}{1+\frac{\beta}{\epsilon}}\right)$$

$$S_L = \frac{w_L L}{PQ} = (\gamma_L + \gamma_{LL} lnL + \gamma_{LS} LnS + \gamma_{LK} lnK) (1-\frac{\alpha}{\eta}) \tag{35}$$

$$S_K = \frac{w_K K}{PQ} = (\gamma_K + \gamma_{KL} lnL + \gamma_{KS} LnS + \gamma_{KK} lnK) (1-\frac{\alpha}{\eta})$$

Due to the small number of degrees of freedom with this specification the model would not estimate well, therefore, the generalized three input Cobb-Douglas production technology (Beattie and Taylor 1985) is employed. The functional form of this production function is:

$$Q = \alpha_0 L^{\alpha_1} S^{\alpha_2} K^{\alpha_3} \tag{36}$$

and the share equations are:

$$\begin{aligned} S_L &= \alpha_1 * (1 - \frac{\alpha}{\eta}) \\ S_K &= \alpha_3 * (1 - \frac{\alpha}{\eta}) \\ S_S &= \alpha_2 * [\frac{1 - \frac{\alpha}{\eta}}{1 + \frac{B}{\epsilon}}] \end{aligned} \tag{37}$$

The share equations together with the output demand, the inverse input supply, and the production function equations become the full estimatable model.

Profit Function

The dual model utilizes the generalized Leontief profit function (Chambers 1988):

$$\Pi^s(P, W^*, W_1) = -[B_{00}P + 2P^{.5} \sum_{j=L,S,K} B_{0j} W_j^{.5} + \sum_{j=L,S,K} \sum_{i=L,S,K} B_{ij}(W_i W_j)^{.5}] \tag{38}$$

This profit function is chosen since it is a second-order approximation of the actual profit function and because it possesses a number of desirable characteristics for empirical analysis. It is in a class of so-called flexible functional forms which carries few *a priori* restrictions on the technology than specific forms, while maintaining features consistent with profit maximization.

This profit function becomes the shadow profit function by replacing P with $P\varrho_P$ and W_S with $W_S\varrho_W$. Where $\varrho_P = (1 - \frac{\alpha}{\eta})$ and $\varrho_W = (1 + \frac{\beta}{\epsilon})$. Using Hotelling's shadow price lemma on the shadow profit function gives the following optimal input and output functions:

$$L = \beta_{11} + \beta_{01}\left(\frac{P\varrho_P}{W_L}\right)^{.5} + \beta_{21}\left(\frac{W_K}{W_L}\right)^{.5} + \beta_{31}\left(\frac{W_s\varrho_W}{W_L}\right)^{.5}$$

$$K = \beta_{22} + \beta_{02}\left(\frac{P\varrho_P}{W_K}\right)^{.5} + \beta_{21}\left(\frac{W_L}{W_K}\right)^{.5} + \beta_{32}\left(\frac{W_s\varrho_W}{W_K}\right)^{.5}$$

$$S = \beta_{33} + \beta_{03}\left(\frac{P\varrho_P}{W_S\varrho_W}\right)^{.5} + \beta_{31}\left(\frac{W_L}{W_S\varrho_W}\right)^{.5} + \beta_{32}\left(\frac{W_K}{W_S\varrho_W}\right)^{.5} \qquad \textbf{(39)}$$

$$Q = -\left[\beta_{00} + \beta_{01}\left(\frac{W_L}{P\varrho_P}\right)^{.5} + \beta_{02}\left(\frac{W_K}{P\varrho_P}\right)^{.5} + \beta_{03}\left(\frac{W_s\varrho_W}{P\varrho_P}\right)^{.5}\right]$$

Here the symmetry restrictions for the profit function are imposed by equating the coefficients across the output and input equations. All profit functions must also be homogeneous of degree one in prices. This holds for a properly specified Generalized Leontief profit function.

These four equations together with the inverse market supply and output market demand equations give the full dual model.

DATA

Annual data for the years 1970-89 are used. All price and expenditure series are deflated.

For the lumber demand equation, lumber quantity was taken from Western Wood Products Yearbooks (WWPA), the lumber and substitution prices come from the data used in the Renewable Resources Planning Act (RPA) timber assessments for east side Oregon and Washington and value of shipments from interior Canada (Adams et al. 1988 and Chemlick 1995). The construction expenditures are from the Economic Report of the President (1994). Both lumber prices are deflated with the Producer Price Index for materials used in construction. The construction expenditures are deflated with the Consumer Price Index for Housing.

For the inverse stumpage supply equation, the stumpage price is from the RPA for Pacific Northwest eastside. Total harvests are from Oregon State Department of Forestry's Timber Harvest Reports. Public stumpage sold is from Production, Prices, Employment, and Trade in Northwest Forest Industries (Warren, numerous issues). Private inventory is from Pacific Northwest Research Station Resource Bulletins with the years between the inventory dates linearly extrapolated. Stumpage prices were deflated with the Producer Price Index of crude material for further processing.

The quantities of inputs used in the share equations came from numerous sources. The stumpage used by the lumber industry was calculated by: 1) converting lumber and plywood (data from American Plywood Association) production in eastern Oregon to a log scale basis using RPA eastside overrun factors; 2) calculating lumber's share of this total, and 3) applying it to the total harvest figure. The quantity of labor is average annual employment from Oregon's Employment Department statistics for SIC 242 for eastern Oregon (Lux 1995). The capital series is in units of 8-hr capacity and comes from numerous mill studies (Howard numerous editions and Ward 1995) with linear extrapolation between reporting years.

The stumpage cost data, as identified above, is RPA Pacific Northwest eastside. The labor cost data is from Oregon's Employment Department statistics for SIC 242 for eastern Oregon (Lux 1995). The capital cost was calculated by first deducting energy, wage, and miscellaneous costs as reported by Census of Manufactures (Spelter 1995) from RPA total manufacturing cost. Then the percent of total cost used by labor and capital were calculated from the Census and RPA data. The labor percentage was used with the Department of Labor payroll data to provide yearly total cost data to which the capital proportion was applied. The total revenue data for the lumber industry was calculated from the quantity and price information presented above. Labor costs were deflated by using the Index for nonfarm business compensation. The capital cost were deflated with the PPI for capital equipment.

ESTIMATION AND RESULTS

For empirical implementation we assume that all the functions are stochastic and that the errors are additive and jointly normally-distributed with zero mean and constant variance-covariance matrix. Since each of the equations in both models contain endogenous variables on the right-hand side, the use of a simultaneous estimation method is preferred. Both two-stage least squares (2SLS) and three-stage least squares (3SLS) estimation methods provide unique and consistent estimates of the parameters of systems of equations. 3SLS is the preferred method (more efficient) since it is a systems estimator that takes into account information from all the equations in the model as well as the covariance between the equations. 2SLS is a single equation estimation technique so it does not incorporate this information. However, a necessary condition for the superior efficiency of 3SLS over 2SLS is that the specification of all the equations in the model are correct.

Since the models developed here are nonlinear in the parameters the nonlinear variant of 2SLS (NL2SLS) and 3SLS (NL3SLS) are utilized. The theoretically preferred 3SLS method results will be discussed first.

Convergence of the nonlinear estimations were obtained for both models. The starting values for the primal model estimation were the results of the application of ordinary least squares on the production function, the inverse input supply, and output demand equations[4]. Ignoring the share equations in this manner is employing the

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[4]The model also converged to the same results when two-stage-least squares results of the same equations were used as starting values. Other starting values close to

(continued...)

assumption that there is no market power in either the input or output markets (conjectural elasticities = 0). The starting values for the dual model were the results of restricted ordinary least squares on the model with the assumption of no market power. The restrictions were applied to maintain the symmetry restrictions of the profit function.

RESULTS

Primal Model

The full primal model with consistent parameter notation is:

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[4](...continued)
these initial values also converged to the same results. All other converged results had larger convergence criteria than these results, indicating local optima.

$$
\begin{aligned}
&\ln Q = \beta_0 + \beta_1 \ln P + \beta_2 \ln PS + \beta_3 \ln CON \\
&\ln W = \beta_4 + \beta_5 \ln TS + \beta_6 \ln GS + \beta_7 \ln PUB \\
&\ln Q = \beta_8 + \beta_9 \ln L + \beta_{10} \ln S + \beta_{11} \ln K \\
&SL = \beta_9 * \left(1 - \frac{\alpha}{-\beta_1}\right) \\
&SS = \beta_{10} * \left(\frac{1-\dfrac{\alpha}{-\beta_1}}{\left(1+\dfrac{B}{\left(\dfrac{1}{\beta_5}\right)}\right)}\right) \\
&SK = \beta_{11} * \left(1 - \frac{\alpha}{-\beta_1}\right)
\end{aligned}
\tag{40}
$$

The results of the primal model (table 2a and 2b) show that the null hypotheses that the input and output markets are competitive can not be rejected. The asymptotic t-ratios for the conjectural elasticity estimates indicate that the parameters are not significantly different from zero at the .05 level. The large standard error of the input conjectural elasticity, however, does not make it possible to reject an alternative hypothesis that the elasticity is equal to one. Therefore, a monopsonistic input market structure can not be rejected either. Conversely, the data does not support the hypothesis that the output market is monopolistic. The negative sign on the output market conjectural elasticity is not as theorized, but is nevertheless, close to zero.

The results of the other equations and parameters are mixed. All of the parameters in the output market demand equation and the production function have the hypothesized signs with varying degrees of statistical significance. The inverse market supply equation results are the poorest. Both the constant and the public stumpage sold variables are not statistically significant. The remaining variables have the expected signs and are statistically significant at the ten percent level.

Table 2a. Estimated Conjectural Elasticities of the Primal Model using 3SLS.

Conjectural Elasticities	Estimate	Standard Errors	t-ratio $H_0=0$	t-ratio $H_0=1$
Output Market: α	-0.86045	1.0489	-0.820	-1.7737
Input Market: B	1.2999	1.1004	1.1813	0.2725

Table 2b. Estimated Parameters of the Primal Model using 3SLS.

Output Demand Parameters	Estimate	t-ratio
β_0	14.663	19.437
β_1	-0.80514	-2.9182
β_2	0.18378	1.7648
β_3	.67226	5.5776
Inverse Input Supply Parameters		
β_4	-13.834	-1.1459
β_5	2.6240	3.3864
β_6	-3.0942	-3.7304
β_7	0.75773	1.4548

Production Function Parameters		
β_8	3.9602	2.1691
β_9	0.6148	5.4672
β_{10}	0.14839	1.6862
β_{11}	0.025548	1.6715

Dual Model

The full dual model with the output demand and input supply equations and consistent parameters notation is:

$$L = \beta_{11} + \beta_{01}\left(\frac{P(1 - \frac{\alpha}{\beta_1})}{W_L}\right)^{.5} + \beta_{21}\left(\frac{W_K}{W_L}\right)^{.5} + \beta_{31}\left(\frac{W_S\left[1 + \frac{B}{\left(\frac{1}{\beta_5}\right)}\right]}{W_L}\right)^{.5}$$

$$K = \beta_{22} + \beta_{02}\left(\frac{P(1 - \frac{\alpha}{\beta_1})}{W_K}\right)^{.5} + \beta_{21}\left(\frac{W_L}{W_K}\right)^{.5} + \beta_{32}\left(\frac{W_S\left[1 + \frac{B}{\left(\frac{1}{\beta_5}\right)}\right]}{W_K}\right)^{.5}$$

$$S = \beta_{33} + \beta_{03}\left(\frac{P(1 - \frac{\alpha}{\beta_1})}{W_S\left[1 + \frac{B}{\left(\frac{1}{\beta_5}\right)}\right]}\right)^{.5} + \beta_{31}\left(\frac{W_L}{W_S\left[1 + \frac{B}{\left(\frac{1}{\beta_5}\right)}\right]}\right)^{.5} + \beta_{32}\left(\frac{W_K}{W_S\left[1 + \frac{B}{\left(\frac{1}{\beta_5}\right)}\right]}\right)^{.5} \qquad \textbf{(41)}$$

$$Q = -\left[\beta_{00} + \beta_{01}\left(\frac{W_L}{P(1 - \frac{\alpha}{\beta_1})}\right)^{.5} + \beta_{02}\left(\frac{W_K}{P(1 - \frac{\alpha}{\beta_1})}\right)^{.5} + \beta_{03}\left(\frac{W_S\left[1 + \frac{B}{\left(\frac{1}{\beta_5}\right)}\right]}{P(1 - \frac{\alpha}{\beta_1})}\right)^{.5}\right]$$

$$lnQ = \beta_0 + \beta_1\ lnP + \beta_2\ lnPS + \beta_3\ lnCon$$

$$lnW = \beta_4 + \beta_5\ lnTS + \beta_6\ lnGS + \beta_7\ lnPUB$$

Where $(1 - \frac{\alpha}{\beta_1})$ and $\left[1 + \frac{B}{\left(\frac{1}{\beta_5}\right)}\right]$ replaces ϱ_P and ϱ_W, respectively.

Like the primal model, the results of the dual specification (table 3a and b) do not allow the rejection of the null hypotheses of no market power in the input and output markets. Unlike the primal results, however, the hypothesis that the input market is monopsonistic in structure can be rejected. Similar to the primal results, these results do not support the hypothesis that the output market is monopolistic. Of the remaining parameters in the model, only the coefficients on the ratio of labor cost to stumpage cost and public stumpage sold in the supply equation are not statistically significant. Again the negative signs on the conjectural elasticities terms are not as theorized.

Table 3a. Estimated Conjectural Elasticities of the Dual Model using 3SLS.

Conjectural Elasticities	Estimate	Standard Errors	t-ratio $H_0=0$	t-ratio $H_0=1$
Output Market: α	-0.1785	.13567	-1.3175	-8.6883
Input Market: B	-0.043975	.12977	-0.033886	-8.0448

Table 3b. Estimated Parameters of the Dual Model using 3SLS.

Optimal Labor Parameters	Estimate	t-ratio
β_{11}	-3825.7	-2.1745
β_{01}	87843	3.5099
β_{21}	2831.2	3.1928
β_{31}	12774	0.73677
Optimal Capital Parameters		

β_{22}	3473.4	3.2453
β_{02}	-57963	-3.5278
β_{21}	2831.2	3.1928
β_{32}	58263	3.8591
Optimal Stumpage Parameters		
β_{33}	2783100	6.0075
β_{03}	-1110300	-3.1135
β_{31}	12774	0.73677
β_{32}	58263	3.8591
Optimal Output Parameters		
β_{00}	-1531900	-3.1071
β_{01}	87843	3.5099
β_{02}	-57963	-3.5278
β_{03}	1110300	-3.1135
Output Demand Parameters		
β_0	13.564	21.823
β_1	-0.59526	-2.9766
β_2	0.25145	3.1997
β_3	0.57834	5.8612
Inverse Input Supply Parameters		
β_4	-21.349	-2.2577
β_5	2.756	3.6315
β_6	-2.0669	-2.3329
β_7	0.44571	0.99464

As stated earlier, if the specification of any of the equations in a system are incorrect, 3SLS can contaminate the results of the other equations in the system

(Tremblay 1996). Therefore, 2SLS and not 3SLS would be the appropriate estimation technique[5]. Allowing for this possibility, the 2SLS estimates follow (tables 4a,b and 5a,b).

The 2SLS results of the primal model are very similar to the 3SLS results. Only the sign of one coefficient is reversed (the coefficient on the capital variable in the production function). The remaining coefficients are close in value to the 3SLS results with t-ratios mostly being lower. The standard errors of the 2SLS results are all higher as the method mandates.

Table 4a. Estimated Conjectural Elasticities of the Primal Model using 2SLS.

Conjectural Elasticities	Estimate	Standard Errors	t-ratio: $H_0=0$	t-ratio: $H_0=1$
Output Market: α	-0.87200	1.6951	-0.51443	-1.104
Input Market: B	1.2315	1.4727	0.83621	0.15719

Table 4b. Estimated Parameters of the Primal Model using 2SLS.

Output Demand Parameters	Estimate	t-ratio
β_0	14.576	17.157
β_1	-1.067	-3.4349
β_2	0.28086	2.3843
β_3	0.89274	6.1107

[5] 2SLS would be the appropriate technique for the other equations in the model, however, it would also provide inconsistent estimators for the miss-specified equation.

Inverse Input Supply Parameters		
β_4	-16.074	-1.1705
β_5	2.9437	3.3500
β_6	-3.8419	-3.6800
β_7	1.1068	1.7025
Production Function Parameters		
β_8	2.0354	0.79226
β_9	0.73390	4.7538
β_{10}	0.16875	1.1579
β_{11}	-0.030052	1.1520

The 2SLS results of the dual model (tables 5a and b) are also similar to the 3SLS results. All of the parameters have the same signs and two have lower t-values.

Table 5a. Estimated Conjectural Elasticities of the Dual Model using 2SLS.

Conjectural Elasticities	Estimate	Standard Errors	t-ratio $H_0=0$	t-ratio $H_0=1$
Output Market: α	0	0.27887	0	-3.5859
Input Market: B	0	0.21248	0	4.706

Table 5b. Estimated Parameters of the Dual Model using 2SLS.

Optimal Labor Parameters	Estimate	t-ratio
β_{11}	-5010.2	-1.6665
β_{01}	64987	1.6957
β_{21}	2804.8	1.9150

β_{31}	44488	1.5111
Optimal Capital Parameters		
β_{22}	3474.1	2.7692
β_{02}	-58204	-2.7692
β_{21}	2804.8	1.9150
β_{32}	71954	3.3306
Optimal Stumpage Parameters		
β_{33}	2705000	4.3447
β_{03}	-1249200	-2.5575
β_{31}	44488	1.5111
β_{32}	71954	3.3306
Optimal Output Parameters		
β_{00}	-1234900	-2.1551
β_{01}	64987	1.6957
β_{02}	-58204	-2.6487
β_{03}	-1249200	-2.5575
Output Demand Parameters		
β_0	14.093	17.867
β_1	-0.74538	-2.6446
β_2	0.24201	2.1981
β_3	0.65627	4.8193
Inverse Input Supply Parameters		
β_4	-21.094	-1.5435
β_5	2.871	3.4203
β_6	-2.8035	-2.7069
β_7	0.81715	1.2394

DISCUSSION AND SUMMARY

The results of no market power, although not unanimous, are consistent with past studies in the Pacific Northwest. It seems justified to say that the stumpage and lumber markets in eastern Oregon are competitive. The results, however, do not reveal if it has always been this way. Mead (1966) and Mead et al. (1981) found indications of collusive activity in stumpage markets in the early 1960s, but less in the mid 1970s. The results here do not exclude the possibility that the market structure has changed over time. The model results presented here are estimates of the average value of the conjectural elasticities over time. It is possible that market power was exerted in the past, but has disappeared over time. For the input market, this would be consistent with the evidence that logs are flowing further distances.

In the same vein, eastern Oregon has historically been divided into two distinct regions for many timber supply studies (Beuter et al. 1976 and Sessions 1990). The region could be separated into two distinct input market areas--central Oregon and the Blue Mountain regions. These subregions receive 88 per cent and 95 per cent, respectively, of their logs from within their own region (Howard and Ward numerous volumes). This distinction, however, is not maintained for this analysis since all the data needed to estimate the models are not available at this level of disaggregation. If these are two distinct markets in terms of log supply then the results presented here are averages for the two regions and it is possible that one region may be characterized by mills which exert market power in the input markets while the other region does not.

The results indicate that the lumber produced in eastern Oregon is a homogeneous product. Lumber from one part of eastern Oregon will substitute easily for lumber from the other parts of eastern Oregon as well as from other producing regions around the world. Therefore, the geographical split of eastern Oregon is not necessary for this market. These results are consistent with the past studies discussed earlier as well as most knowledgeable peoples' beliefs.

Both the primal and dual methods provide similar conclusions. The primal may be preferred since it does not rely on the assumption that the firms' conjectural elasticities are based on factors exogenous to the firm. This is the assumption that allows the use of Hotelling's lemma to derive the optimal output supply and optimal input demand equations.

Due to the large standard errors of many of the parameter estimates and the incorrect signs on most of the conjectural elasticity estimates it would be desirable to get disaggregated data. Firm-level data would increase the observations and remove the industry aggregation assumptions from the analysis. If this is done a better analysis of the market structure of eastern Oregon's lumber and stumpage markets could be undertaken.

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APPENDICES

APPENDIX A: AGGREGATION

Production Function Aggregation

Aggregating firm-level production functions to an industry production function requires that certain properties be satisfied. To avoid notational clutter consider a one input firm-level production function:

$$q_i = f_i(x_i) \tag{42}$$

For consistency we would like the linear aggregation conditions to hold:

$$f(x) = \sum_{i=1}^{N} f_i(x_i) \qquad x = \sum_{i=1}^{N} x_i \tag{43}$$

where f(x) is the industry production function and x is the total industry output. Differentiating the production function:

$$\frac{\partial f(x)}{\partial x_i} = \frac{\partial f(x)}{\partial x}\frac{\partial x}{\partial x_i} = \frac{\partial f_i(x_i)}{\partial x_i} \tag{44}$$

Thus,

$$\frac{\partial f(x)}{\partial x} = \frac{\partial f_i(x_i)}{\partial x_i} \tag{45}$$

Therefore, aggregation consistency requires that each firm's marginal product equal aggregate marginal product. Moreover, this applies regardless of the level of x_i,thus each firm-level marginal product must be independent of x_i. The reason for this is that from the aggregate perspective, it is irrelevant which firm produces which units of output. For example, if some of the output is redistributed from one firm to another it doesn't affect total output, thus the aggregate marginal product must be the same. The only way for this to be possible is for the marginal products of all firms be the same. Thus aggregate marginal product is independent of aggregate output and is constant. The easiest way to see this is to differentiate the preceding expression with respect to x_j (I≠j) to obtain:

$$\frac{\partial f(x)}{\partial x_i \partial x_j} = \frac{\partial^2 f(x)}{\partial x^2} = 0 \tag{46}$$

Given that each firm's marginal product is equal and constant the first-order condition for the oligopsonist (equation **(16)**) reduces to:

$$\frac{p}{w}\frac{\partial q}{\partial x} = \frac{\beta_i}{\epsilon} + 1 \tag{47}$$

and requires that each firm's conjectural elasticity with respect to the factor demand, β_i, be equal.

Likewise, the first-order condition for the oligopolist reduces to:

$$p\frac{\partial q}{\partial x} - w = p\frac{\partial q}{\partial x}\frac{\alpha_i}{\eta} \tag{48}$$

and shows that each firm's conjectural elasticity with respect to output, α_i, are equal.

While these may seem at first glance to be somewhat restrictive it is satisfied as a consequence of the existence of an equilibrium. Therefore, as long as an equilibrium exists, it must be that the equilibrium value of the conjectural elasticities are the same.

While the same equality conditions of the conjectural elasticities are not forthcoming mathematically from the first-order conditions if the firm possesses market power in the input market and the output market simultaneously, it is not difficult to accept the assumption that they are (Azzam and Pagoulatos). The first order condition then becomes:

$$p\frac{\partial q}{\partial x}(1-\frac{\alpha}{\eta}) = w(1+\frac{\beta}{\epsilon}) \tag{49}$$

Cost Function Aggregation

Aggregation consistency (as described by Chambers 1988) requires the linear aggregation of the individual firms' cost functions:

$$c(w,q) = \sum_{i=1}^{N} c_i(w,q_i) = c(w,q_1,q_2,\ldots,q_m) \tag{50}$$

Except for the most trivial cases, each firm will operate or want to operate at a different output level. Output generally enters individual cost functions in a nonlinear and at times quite complicated fashion. Using equation **(43)** as the appropriate definition of industry output (the simple, unweighted sum of each firm's output):

$$q = \sum_{i=1}^{N} q_i \tag{51}$$

Then any functional form satisfying both ((**50**)) and ((**51**)) is capable of being an industry cost function. When c(w,q) is consistent with these conditions, however, the class of candidate functions is considerably restricted. Differentiation of c(w,q) with respect to q_i yields:

$$\frac{\partial c(w,q)}{\partial q} = \frac{\partial c_i(w,q_i)}{\partial q_i} \quad \forall i \tag{52}$$

$$\frac{\partial c(w,q)}{\partial q_i} = \frac{\partial c(w,q)}{\partial q}\frac{\partial q}{\partial q_i} = \frac{\partial c_i(w,q_i)}{\partial q_i} \tag{53}$$

since $\partial q/\partial q_i = 1$.

Directly related to the firm's marginal product, aggregation consistency requires that each firm-level marginal cost equal aggregate marginal cost and that it applies regardless of the level of q_i and that each firm-level marginal cost is independent of q_i. Therefore, aggregate marginal cost is independent of aggregate output. This can be seen by differentiating the preceding expression with respect to q_j ($i \neq j$):

$$\frac{\partial^2 c(w,q)}{\partial q_i \partial q_j} = \frac{\partial^2 c(w,q)}{\partial q^2} = 0 \tag{54}$$

Letting $\lambda(w)$ represent aggregate marginal cost,

$$\lambda(w) = \frac{\partial c(w,q)}{\partial q} \tag{55}$$

and integrating over q gives

$$c(w,q) = \lambda(w)q + c^*(w), \tag{56}$$

where $c^*(w)$ is a constant of integration.

where $c^*(w)$ is a constant of integration.

Expression ((**56**)) says that an aggregate cost function that is consistent with ((**50**)) must be consistent with a quasi-homothetic technology. More specifically, the aggregate cost function must be affine in output, that is, a translation of a linear function of aggregate output. However, the property that $c(w,0)=0$ requires that $c^*(w)$ itself equals zero, in which case the function would be consistent with the linear homogeneity of production. Therefore, if we seek to define an aggregate cost function that depends on total industry output and satisfies all of the properties of $c(w,q)$, we have a linearly homogeneous technology. However, $c^*(w)$ can also be seen to represent fixed costs and $c(w,q)$ can be interpreted as a short-run cost function. In this case equation (**56**) implies quasi-homotheticity and the associated production functions must have expansion paths that are straight lines but that do not ultimately emanate from the origin.

APPENDIX B: MULTICOLLINEARITY IN PRIMAL MODEL I

This appendix shows the perfect multicollinearity that is present when attempting to estimate the optimality condition of primal model I with a constant elasticitity demand function. The optimality condition (equation 26) is:

$$w = \theta_1[p(\frac{\partial Q}{\partial X})] + \theta_2[\frac{\partial P}{\partial Q}\frac{\partial Q}{\partial X}Q] - \theta_3[\frac{\partial w}{\partial X}X] \tag{57}$$

if we let $\eta = -\frac{\partial Q}{\partial P}\frac{P}{Q}$

so that $\frac{\partial Q}{\partial P} = -\eta\frac{Q}{P}$

and $\frac{\partial P}{\partial Q} = -\frac{1}{\eta}\frac{P}{Q}$

and let $\alpha = \frac{\partial Q}{\partial X}\frac{X}{Q}$ and $\frac{\partial Q}{\partial X} = \alpha\frac{Q}{X}$

we see that:

$$w = \theta_1\alpha\frac{Q}{X}P - \theta_2\frac{P}{Q}\frac{1}{\eta}\alpha\frac{Q}{X}Q - \theta_3\frac{\partial w}{\partial TX}X \tag{58}$$

Combining terms we get:

$$w = \theta_1\alpha\frac{QP}{X} - \theta_2\alpha\frac{QP}{X}\frac{1}{\eta} - \theta_3\frac{\partial w}{\partial TX}X \tag{59}$$

As can be seen, when the elasticity of demand (η) is constant we have perfect multicollinearity between the first two terms on the right of the equality sign and the equation will not estimate.

APPENDIX C: PROOF OF MARGINAL PRODUCT

Show $\dfrac{\partial Q}{\partial X} = \dfrac{\partial lnQ}{\partial lnX}\dfrac{Q}{X}$.

Take as an example the Cobb-Douglas production function:

$$Q = \alpha_0 X_1^{\alpha_1} X_2^{\alpha_2}$$

$$\frac{\partial Q}{\partial X_1} = \alpha_1 \alpha_0 X_2^{\alpha_2} X_1^{\alpha_1 - 1}$$

$$lnQ = \alpha_{00} + \alpha_1 lnX_1 + \alpha_2 lnX_2$$

$$\frac{\partial lnQ}{\partial lnX_1} = \alpha_1$$

$$\frac{\partial Q}{\partial X_1}\frac{X_1}{Q} = [\alpha_0 \alpha_1 X_2^{\alpha_2} X_1^{\alpha_1 - 1}]\frac{X_1}{Q} = \alpha_0 \alpha_1 X_2^{\alpha_2} X_1^{\alpha_1 - 1} X_1^1 \frac{1}{Q} \tag{60}$$

$$= \alpha_0 \alpha_1 X_2^{\alpha_2} X_1^{\alpha_1} \frac{1}{Q} = \alpha_0 X_1^{\alpha_1} X_2^{\alpha_2} \frac{1}{Q} \alpha_1$$

$$= \frac{Q}{Q}\alpha_1$$

$$= \alpha_1$$

$$= \frac{\partial lnQ}{\partial lnX_1}$$