NCEE

NATIONAL CENTER FOR ENVIRONMENTAL ECONOMICS

Estimating Welfare Effects from Supply Shocks with Dynamic Factor Demand Models

Adam Daigneault and Brent Sohngen

Working Paper Series

Working Paper # 08-03
February, 2008

U.S. Environmental Protection Agency
National Center for Environmental Economics
1200 Pennsylvania Avenue, NW (MC 1809)
Washington, DC 20460
http://www.epa.gov/economics

Estimating Welfare Effects from Supply Shocks with Dynamic Factor Demand Models

Adam Daigneault and Brent Sohngen

NCEE Working Paper Series

Working Paper # 08-03
February, 2008

Estimating Welfare Effects from Supply Shocks with Dynamic Factor Demand Models*

Adam J. Daigneault
National Center for Environmental Economics
US Environmental Protection Agency
1200 Pennsylvania Ave., NW (MC 1809T)
Washington, DC 20460
202-566-2348 (Office)
202-566-2338 (Fax)
Daigneault.Adam@epa.gov

Brent Sohngen
The Ohio State Univesity
Dept. of Agr., Env. and Dev. Economics
Sohngen.1@osu.edu

* The authors would like to thank Richard Haynes, Darius Adams, and Ian Lange for their thoughtful comments and suggestions on earlier drafts of this paper. The views expressed in this paper are those of the authors and do not necessarily reflect those of the Environmental Protection Agency.

Abstract

This paper examines how the demand for commodities adjusts to supply shocks, and shows the importance of capturing this adjustment process when calculating welfare effects. A dynamic capital adjustment model for U.S. softwood stumpage markets is developed, and compared to a traditional lagged adjustment model. The results show that timber markets in the U.S. adjusted to the large supply shock of the late 1980's over a 5 to 8 year period. Our short-run price elasticity estimates are similar to the existing literature, ranging from -0.002 to -0.253, although our estimates show that the demand is substantially more elastic in the long-run, with long-run elasticity estimates ranging from -0.134 to -0.506. If this adjustment in the demand function is taken into account when calculating welfare effects, the effects of the supply shock in timber markets of the late 1980's on consumer surplus declines by over 50% compared to the estimated effects when using the short-run model, and the total welfare effects decline by 37%.

Keywords: dynamic adjustment, environmental regulation, price elasticity, regional timber markets, structural change, stumpage demand, timber supply

Subject Area: Forests (25), Environmental Policy (52), Economic Impacts (59)

Introduction

A key issue in the economics of natural resource scarcity revolves around the effect of supply shocks on prices and welfare. Elasticity estimates for many commodities are typically found to be highly inelastic (e.g., Wear and Murray 2004; Bohi 1981; Krichene 2002), suggesting that disruptions to supply will have large effects on prices, and consequently on consumer surplus. Most econometric studies, however, focus on short-run adjustments and fail to consider how long the adjustment to the long run might take, and what effects this adjustment may have on welfare estimates. While it is widely acknowledged that the price elasticity of demand should become more elastic over time (Samuelson 1947), few studies examine just how quickly demand elasticity changes, and what the consequences of this change in elasticity are for welfare estimates.

A difference between the short run and long run price elasticity depends on a given market's ability to effectively substitute factors of production (capital, labor, raw materials, etc.) over time. In the short run, some factors of production are typically fixed (e.g., capital). When supply shocks occur, firms face constraints associated with adjusting their inputs to achieve the optimal mix of inputs. Only in the longer run, after input constraints are no longer binding, are firms able to substitute across all factors of production and reach the optimal cost minimization (profit maximization) point. As these quasi-fixed factors become "unstuck," it is expected that the demand for the factors that are less-costly-to-change (i.e. have low transaction costs) will become more elastic. Theoretically, the notion that price elasticity becomes greater in the long run has been explained with Samuelson's (1947) adaptation of the Le Chatelier principle. Understanding the extent to which short and long run elasticity estimates change has important implications for natural resource policy. Industries that can adjust fairly quickly are likely to have smaller welfare impacts with supply shocks compared to industries that adjust more slowly.

When measuring welfare effects of supply shocks, it is important to carefully measure the entire adjustment process. Relying on short-run demand estimates can potentially overstate the welfare effects because the resulting price changes will be too large. While one would expect markets to adjust in the long-run, focusing on long-run estimates could have the opposite effect, e.g., estimates of welfare effects could be too small. It is important to account for the entire adjustment process in elasticity in order to trace the welfare effects over time.

This paper presents methods for estimating the short run and long run elasticities and ensuing welfare effects associated with a natural resource supply shock. We focus on timber stumpage markets, and examine the effects of the reduction in federal timber harvests from the western U.S. that occurred in the late 1980's primarily because the northern spotted owl was listed on the Endangered Species List, but also because of changing interregional trends in forest resources and various trade policies between Canada and the US. These supply shocks had the immediate impact of reducing the supply of timber by around 15% nationally (Wear and Murray 2004). To show the importance of correctly accounting for adjustments in demand elasticity, a lagged adjustment model following Houthakker and Taylor (1970) is estimated and compared to estimates from a dynamic factor market adjustment model. By comparing these models, we show how to trace the adjustment in price elasticity over time in response to a supply shock. Results from both models are used to calculate and compare welfare effects.

This research expands the existing literature in several ways. First, most demand analyses assume static equilibriums, and consequently, studies over the years have found that timber stumpage demand is highly inelastic. The dynamic demand analysis conducted here shows that the Le Chatelier principle holds for forestry markets, and that demand will become more elastic as the market adjusts to a supply shock. Second, we are able to measure rates of investment in capital in the forest products industry. We find that capital adjustment in the forestry sector appears to be slower than in other industries of the economy, but even this slower adjustment moderates estimated welfare effects. Third, most economic assessment of the effects of supply shocks indicate that substantial welfare effects occur in the short run, however, since capital is found to turn-over within 5-10 years, and substantial supply shocks similar to our empirical example can persist, analysts should be careful measuring welfare effects over several years from models constructed on static equilibriums. For other commodities that have even quicker capital turn-over rates, it may be equally important to use the dynamic methods here when estimating welfare effects.

Literature Review

Within the literature, there have been a number of attempts to assess differences between short and long run elasticities. Koyck (1954) and Houthakker and Taylor (1970) recommended using a lagged adjustment model, however, as noted by Bohi (1981), the empirical results from lagged adjustment models are known to be highly sensitive to variations in the model specification, causing estimates of both SR and LR elasticities to be erratic. A more recent development in factor demand estimation is the work of Berndt, Fuss, and Waverman (1977, 1980), who showed how to estimate the dynamic factors of demand for energy using a cost adjustment approach. They explicitly incorporated dynamic optimization into an econometric model of factor demand to allow the calculation of well-defined measures of short, intermediate, and long run elasticities. Their study showed how long run elasticity estimates differ from short run elasticity estimates due to adjustments in capital in the industry of interest.

Many of the studies of the U.S. timber and wood production market have assumed a static equilibrium, or instantaneous factor adjustment. Most research in timber markets has focused on estimating econometric models of regional stumpage markets (Robinson 1974; Adams and Haynes 1980; Newman 1987). Other studies have considered the implications of specific policies (Brown and Zhang 2005; Wear and Murray 2004; and Sun 2006). For the most part, timber market studies have found stumpage demand to be price inelastic (table 1). Few studies using dynamic factor demand estimation techniques have been applied to the U.S. timber and wood products sector. Merrifield and Singleton (1986) use a dynamic capital adjustment model to describe the Pacific Northwest lumber and plywood industries under the assumption that firms are cost minimizers. They find that the short run price elasticities of demand for stumpage in both industries is low (-0.007 for lumber and -0.103 for plywood), and respond little to the adjustment in capital over time, with long run elasticities of only -0.023 for lumber and -0.105 for plywood. Stevens (1995) uses panel data from the sawmill industry in Western Washington to estimate a dynamic demand model for firms that are profit maximizers, and finds that the elasticity of demand for sawlogs increases from -0.183 in the short run to -0.467 in the long run.

The Lagged Adjustment Model

Following standard theory, **t**he regional demand for softwood stumpage in a given supply region is derived from the production of final goods, and can be specified using the framework of production theory. For region *i*, Q_{it} is the aggregate output produced by all mills in the region i, where $Q_{it} = f(S_{it}, L_{it}, K_{it})$. The function $f(\cdot)$ is a fixed-factor production function with inputs of stumpage (S_{it}), labor (L_{it}), and capital (K_{it}) used by firms in period t. For simplicity, we assume that each region has a single, perfectly competitive market, so that each mill faces the same input costs. The region's aggregate profit function is defined as:

(1) $$\pi_{it} = \max_{p_{it}, w_{it}, r_{it}} P_{it} Q_{it}^{*} - p_{it} S_{it} - w_{it} L_{it} - r_{it} K_{it}$$

where P_{it} is the regional product price, Q^{*}_{it} is the optimal amount of output for the end product, and p_{it}, w_{it} *and* r_{it} are the respective input costs of stumpage, labor, and capital. Applying Hotelling's lemma, region i's derived demand for stumpage is a function of the demand for its output and the prices of all factors of production:

(2) $$S_{it}^{D} = f(p_{it}, w_{it}, r_{it}, P_{it})$$

where S^{D}_{it} is the stumpage demand in region i at time t.

To measure how firms are adjusting their production process over time, a one period lag for the quantity of stumpage demanded (S^{D}_{it-1}) is added to the econometric model that empirically estimates the regional derived demand functions. This formulation is commonly referred to as the lagged adjustment model first derived by Koyck (1954) and is consistent with the model suggested by Houthakker and Taylor (1970), who show that the optimal amount of the consumption good (S_t*) is specified as a function of its price (p_t) and other variables ($\mathbf{Z}_t$) along with a disturbance term (ε_t), such that the demand equation is:

$$(3) \qquad S_t^D = a_0 + a_1 p_t + \sum_{j=2}^{n} a_j Z_{jt} + \varepsilon_t$$

Equation (3) can then be put in an operational form that only contains observable variables such that an adjustment process relating actual and desired input is observed, as expressed in the following equation:

$$(4) \qquad S_t^D = S_{t-1}^D + \gamma(S^{D*} - S_{t-1}^D) \;\; for \;\; 0 < \gamma \leq 1$$

This indicates that in the current period, t, the firm will only adjust a part of the way from the initial condition (S_{t-1}) to the desired condition (S_t*) in response to a change in input prices. The closer that γ is to unity, the faster the adjustment process. Combining (3) and (4), we get:

$$(5) \qquad S_t^D = \gamma a_0 + \gamma a_1 p_t + (1-\gamma)S_{t-1}^D + \gamma \sum_{j=2}^{n} a_j Z_{jt} + \varepsilon_t$$

Incorporating our knowledge about the regional demand for stumpage, we can then formulate regional derived demand curves, where p_t is the input price for stumpage and $\mathbf{Z}_{jt}$ are other factors of derived demand, specifically capital, wage, and the price of lumber. The parameters estimated in equation (5) can then be used to determine short-run and long run elasticities, where $a_1\gamma$ is the short run response and $a_1\gamma/[1-(1- \gamma)]$ is the long run response to a change in price.

Empirical Lagged Adjustment Model

The lagged adjustment model is estimated empirically for three major timber supply regions that are distinguished by their final end products, tree species, and owner composition. The supply and demand system for two Pacific Northwest regions, divided between east and west by the Cascade Mountains, are both dominated by the sawmill industry, yet differ in species and composition. The model for the South includes supply and demand equations for both the sawmill and the pulp and paper industries, as they each contribute to a large portion of the region's timber sector.

Equation (5) is the industry-specific demand function, which is defined above. The supply-side in stumpage markets is individual landowners, including both private and governmental sources, who have production functions that depend on the biological growth and other factors of production. Suppliers require labor, and capital stock (standing inventory) to produce their desired amount of output, which is in turn demanded by the mills in order to produce their final good. For the two Pacific Northwest regions (PNWW and PNWE), we also include a dummy variable (*D89*) equal to 1 for the years greater or equal to 1989 and 0 otherwise, as it acts as a fixed effect for the supply shift caused by federal timber restrictions in the 1990s. In the case of the South, where federally owned forests supply little timber, the price of sawnwood or pulpwood stumpage is included to test for a potential substitution effect. The aggregate supply function for all forest owners in a region is expressed as:

(6) $$S_{it}^{S} = f(p_{it}^{s}, w_{it}^{f}, k_{it}^{f}, Y_{it}^{f})$$

where $S^S{}_{it}$ is the total amount of stumpage demanded in a region i at time t, w_{it}^f is the hourly wage of a logger, k_{it}^f is the standing merchantable inventory (million ft^3) and Y_{it} is the region-specific supply shifter that is discussed above. Merchantable inventory is the inventory in age classes nearing or above the optimal rotation period.

The regional derived demand equations for the Pacific Northwest (ignoring the pulp markets) are estimated using a demand and supply system. The demand equation uses the factors derived in equation (5). The supply equation uses the variables defined in equation (6) but does not include a lagged dependent variable because capital on the supply side, merchantable forest stock, is determined over a substantially longer time period. This system is defined as:

$$(7) \qquad \begin{aligned} S_{it}^S &= \alpha_0 + \alpha_1 p_{it}^s + \alpha_2 k_{it}^{f,merch} + \alpha_3 w_{it}^f + \alpha_4 D89_{it} + \varepsilon_{it} \\ S_{it}^D &= \beta_0 + \beta_1 p_{it}^s + \beta_2 P_{it}^s + \beta_3 w_{it}^s, + \beta_4 k_{it}^s + \beta_5 S_{it-1}^D + v_{it} \end{aligned} \qquad i = PNWW,\ PNWE$$

where p_{it}^s is the volume-weighted average real price for stumpage per thousand board feet (MBF), P_{it}^s is a the real regional price of lumber (\$/MBF), w_{it}^s is the real regional hourly wage rate for sawmill workers, and k_{it}^s is amount of capital stock in billions of dollars. On the supply side, $k_{it}^{f,merch}$ is the amount of merchantable forest stock (million ft^3) for the region, and w_{it}^f is the real hourly wage rate of loggers. All prices and input costs are deflated to 1982 dollars to be consistent with estimates from the previous literature. The respective error terms for the supply and demand equations are ε_{it} and v_{it}. The market clearing condition is that quantity supplied ($S^S{}_{it}$) equals quantity demanded ($S^D{}_{it}$), and is measured in million cubic feet.

For the South, both the sawnwood and pulpwood markets are considered:

$$
(8) \qquad
\begin{aligned}
S_{St}^{SawS} &= \alpha_0 + \alpha_1 p_{St}^{s} + \alpha_2 k_{St}^{f,merch} + \alpha_3 w_{St}^{f} + \alpha_4 p_{St}^{p} + \varepsilon_{St}^{s} \\
S_{St}^{SawD} &= \beta_0 + \beta_1 p_{St}^{s} + \beta_2 P_{St}^{s} + \beta_3 w_{St}^{s}, + \beta_4 k_{St}^{s} + \beta_5 S_{St-1}^{SawD} + v_{St}^{s} \\
S_{St}^{PulpS} &= \delta_0 + \delta_1 p_{St}^{p} + \delta_2 k_{St}^{f,tot} + \delta_3 w_{St}^{f} + \delta_4 p_{St}^{s} + \varepsilon_{St}^{p} \\
S_{St}^{PulpD} &= \varphi_0 + \varphi_1 p_{St}^{p} + \varphi_2 P_{St}^{p} + \varphi_3 w_{St}^{p}, + \varphi_4 k_{St}^{p} + \varphi_5 S_{St-1}^{PulpD} + v_{St}^{p}
\end{aligned}
$$

In this system, $k^{f,tot}$ is the total forest stock on privately owned land (million ft^3), p^p is the real stumpage price for pulplogs (\$/cord), P^p is the real price for processed pulp (\$/cord), w^p is the hourly wage rate for pulp and paper mill workers, and k^p is the amount of real capital stock in the region's pulp and paper industry. The rest of the variables are defined above, and are the same as the Pacific Northwest region. Details on the data and sources used to estimate the regional demand systems for this lagged adjustment model are listed in table 2.

Three-stage least squares (3SLS) was used to estimate each region separately. All of the exogenous independent variables, including the lagged quantity, were used as instruments, and parameter estimates are provided in the results section. These estimates are then used to calculate the region's short run and long run elasticities using the sample means of the data, which was compiled annually from 1950 to 2001. The parameter estimates are listed in table 3, and demand elasticities using the sample means are shown in table 5.

Dynamic Capital Adjustment Model

The theoretical dynamic capital adjustment model follows the model developed by Berndt, Fuss and Waverman (1977, 1980). In this model, the forest and wood products industry is divided into three sub-sectors, stumpage supply, and sawlog and pulplog demand. To analyze how each producer interacts with the other sectors of the market, it is necessary to specify individual profit functions for each producer, and then use these functions to derive the sectors' supply of products and their resulting factors of demand for production. This allows us to construct a system of equations characterizing each market that includes a supply equation, a demand equation, and an equilibrium condition for the major timber supply regions.

Firms are assumed to maximize their profit in the short run with respect to the variable input factor prices conditional on a fixed level of at least one of the inputs, in this case capital. Capital is fixed in the short run because of the adjustment costs that a firm faces when changing the level of capital stock. In the long run, firms do not face this adjustment cost and are able to adjust their share of capital inputs towards a steady state condition, K^*, so that they can maximize the present value of the future stream of profits with respect to the capital stock and gross investments.

In this model, we assume that all stakeholders in a given sector of the forestry and wood products industry (i.e. landowners, sawmills, or pulpmills) face perfect competition and are homogeneous. A representative firm's short run profit equation can then be written as a function of prices and the capital stock, $\pi_{SR} = \max \pi(P, \mathbf{w}; k)$, where P is the output price, $\mathbf{w}$ is a vector of variable inputs (raw materials, labor, etc.), and k is the capital stock. Applying Hotelling's lemma allows us to calculate the conditional short run profit maximizing supply and demand functions, S^S and S^D, respectively. The forest owners' standing inventory is assumed fixed, but capital stocks in the sawmill and pulp and paper industries are allowed to adjust over time.

The long run dynamic optimization problem for these sectors is defined as:

(9) $$\max \int_0^\infty [\pi(P, \mathbf{w}; k) - u(r+\delta)k - c(\dot{k})]e^{-rt}dt$$

where π(•) is the profit function, u is the asset price of capital that is a function of the discount rate, r, and the depreciation rate, δ; and $c(\dot{k})$ is the adjustment cost of capital, which is a function of investment, or the change in capital, $\dot{k}$. Using Euler's equation of the calculus of variation, the first-order condition of (9) for the quasi-fixed input is:

(10) $$\pi_k = u(r+\delta) + rc_{\dot{k}} - c_{\dot{k}\dot{k}}\ddot{k}$$

where π_k is the first derivative of the profit function with respect to k and $\ddot{k}$ is the derivative of the net capital investment with respect to time.

In the long run, we assume that the capital stock fully adjusts to its optimal steady-state level of input, k^*. In this case, the annual investment ($\dot{k}$) and change in investment ($\ddot{k}$) will be equal to zero. If we also assume that adjustment costs are zero when no investment occurs, the first order condition becomes:

(11) $$\pi_k^*(k^*, \dot{k} = 0) = u(r+\delta)$$

where π_k^* is the first derivative of the profit function with respect to k and k^* is the optimal level of capital stock. Equation (11) can also be interpreted as the well-known static condition where the marginal return to capital is equal to the user cost of capital.

The demand function for the capital good can then be formalized by linearly approximating equation (11) around the long run optimal capital stock, k^*, in a manner first presented by Lucas (1967). This method obtains a second order differential equation that can be solved for its stable root, λ, resulting in the following equation:

(12) $\dot{k} = \lambda(k^* - k)$

where $\lambda = -1/2\{r - (r^2 - 4\pi_{kk} / c_{\ddot{k}\ddot{k}})^{1/2}\}$ is a stable root is between zero and one, where zero implies no adjustment and one implies full adjustment in that given time period (Treadway 1971; 1974). Because discrete annual changes will be used to determine empirical estimates, it is more convenient to rewrite equation (12) using discrete time subscripts such that the demand equation for capital is:

(13) $k_{t+1} = \lambda k^* + (1-\lambda)k_t$

Equation (13) is the foundation of our capital adjustment equation, where λ is a parameter directly estimated in the empirical dynamic factor demand system. Equation (13) and the specified supply and demand equations can be used to empirically estimate the dynamic factors of demand and resulting short, intermediate, and long run elasticities for the two production sectors of the wood products industry.

Empirical Dynamic Capital Adjustment Model

Specified functional forms of the profit and capital adjustment cost equations are necessary to empirically estimate the factor demands and resulting elasticities. Quadratic functions are chosen as approximations of the true profit functions because of their flexible functional form. For the empirical specification, superscripts $i = f, s$, and p are used to distinguish between the three sectors: forest owners, sawmills, and the pulp and paper industry, respectively. Capital inputs are identified by k^i and considered to be the only quasi-fixed inputs in the demand system, and w indicates variable inputs. Time indexation is denoted by *t,* and is only used to distinguish between lead and lag variables. For the sawmill and pulp and paper industry, the respective profit functions are:

$$
(14)\quad
\begin{aligned}
\pi^s &= \beta_0 + \beta_P P^s + \sum_i \beta_{Pi} P^s w_i^s + \beta_{Pk} P^s k^s + 0.5\beta_{PP}(P^s)^2 + \beta_z Z^s + \sum_i \beta_{zi} Z^s w_i^s + \beta_{Zk} Z^s k^s \\
&+ 0.5\beta_{ZZ}(Z^s)^2 + \beta_k k^s + \sum_i \beta_{ki} k^s w_i^s + 0.5\beta_{kk}(k^s)^2 + \sum_i \beta_i w_i^s + 0.5\sum_i\sum_j \beta_{ij} w_i^s w_j^s \quad i = s,l \\
\pi^p &= \varphi_0 + \varphi_P P^p + \sum_i \varphi_{Pi} P^p w_i^p + \varphi_{Pk} P^p k^p + 0.5\varphi_{PP}(P^p)^2 + \varphi_z Z^p + \sum_i \varphi_{zi} Z^p w_i^p + \varphi_{Zk} Z^p k^p \\
&+ 0.5\varphi_{ZZ}(Z^p)^2 + \varphi_k k^p + \sum_i \varphi_{ki} k^p w_i^p + 0.5\varphi_{kk}(k^p)^2 + \sum_i \varphi_i w_i^p + 0.5\sum_i\sum_j \varphi_{ij} w_i^p w_j^p \quad i = p,l
\end{aligned}
$$

where subscripts $i = s,p,l$ denote the inputs of sawlogs, pulpwood, and labor, respectively, P^s indicates the market price for lumber, P^p is the final product price for pulp, and Z^i is an exogenous shifter specific to a region's supply or demand equation.

The aggregate supply function for forest owners in a given region is the same as equation (6). The regional derived demand equations for stumpage are determined by applying Hotelling's lemma to equation (14), such that the supply and demand system is:

$$
(15)\quad
\begin{aligned}
S_s^S &= \alpha_s + \alpha_{ss} w_s^s + \alpha_{sl} w_l^f + \alpha_{sk} k^f + \alpha_{sz} Z^f \\
S_s^D &= \beta_s + \beta_{sP} P^s + \beta_{ss} w_s^s + \beta_{sl} w_l^s + \beta_{sk} k^s + \beta_{sz} Z^s \\
S_p^S &= \delta_p + \delta_{pp} w_p^p + \delta_{pl} w_l^f + \delta_{pk} k^f + \delta_{pz} Z^f \\
S_p^D &= \varphi_p + \varphi_{pP} P^p + \varphi_{pp} w_p^p + \varphi_{pl} w_l^p + \varphi_p k^p + \varphi_p Z^p
\end{aligned}
$$

where S_s^D is the sawmills' demand for sawlogs, S_p^D is the pulp and paper industry's demand for pulplogs, and S_s^S and S_p^S are the forest landowners respective annual supply of sawlogs and pulplogs. Using equation (11), where the marginal return to capital is equal to the user cost of capital[1], the long run optimal capital stock (k^*) can be derived from (14):

[1] For this model, the user cost of capital is calculated as a function of the investment producer price index (ppi_{inv}), the general ppi (ppi_{tot}), the interest rate (r), and a constant depreciation rate (δ), such that:

$$U_t^i = \frac{ppi_k^i}{ppi_{total}^i}(r + \delta^i), i = s, p$$

$$
(16) \qquad \begin{aligned} k^{s*} &= \frac{1}{\beta_{kk}}\left[u^s(r+\delta) - \beta_k - \beta_{kP}P^s - \beta_{ks}w_s^s - \beta_{kl}w_l^s\right] \\ k^{p*} &= \frac{1}{\varphi_{kk}}\left[u^p(r+\delta) - \varphi_k - \varphi_{kP}P^p - \varphi_{kp}w_p^p - \varphi_{kl}w_l^p\right] \end{aligned}
$$

Substituting k^{s*} and k^{p*} into equation (13) forms the demand function for capital at the end of period t for the sawmill and pulp and paper industries:

$$
(17) \qquad \begin{aligned} k_{t+1}^s &= \frac{\lambda^s}{\beta_{kk}}\left[u^s(r+\delta) - \beta_k - \beta_{kP}P^s - \beta_{ks}w_s^s - \beta_{kl}w_l^s\right] + (1-\lambda^s)k_t^s \\ k_{t+1}^p &= \frac{\lambda^p}{\varphi_{kk}}\left[u^p(r+\delta) - \varphi_k - \varphi_{kP}P^p - \varphi_{kp}w_p^p - \varphi_{kl}w_l^p\right] + (1-\lambda^p)k_t^p \end{aligned}
$$

Combining equations (15) and (17), we now have a complete system of equations that allows us to derive the responses in supply and demand to price changes in the short, intermediate, and long run. As in the case of the lagged adjustment model, the system of equations for the two Pacific Northwest regions only include the sawtimber industry, while the South accounts for both sawlog and pulplog markets.

To also be consistent with the lagged adjustment model, region-specific exogenous supply and demand variables were included in the system of equations. Exogenous variables in the regional supply equations were the same as the lagged adjustment model. Real gross domestic product per capita (*GDP*, in 1982$) is included in the demand equations to test for any potential income or growth effects on regional demand. A detailed explanation of the data and the sources where each regional statistic was obtained for 1950-2001 is listed in table 2. All data was listed at the regional level with the exception of capital stock, which was disaggregated by multiplying the proportion of a region's production relative to national production by the national measure of capital stock. The annual changes in estimated regional capital stock values were then verified using regional annual investment data that is still published on an annual basis (U.S. Bureau of Labor Statistics 2005). Regional parameter estimates are shown in table 4.

The short run demand responses can be interpreted simply by the parameter estimates for α, δ, β and φ. Because this is a linear demand function, short run elasticity is simply dS/dp($\overline{w}_s^p / \overline{S}$), where $\overline{w}_s^p$ is average price, and $\overline{S}$ is average quantity . The intermediate run (IR) elasticity for stumpage price in the sawmill sector is then calculated as follows:

(18) $$\frac{\partial S_s^{D,IR}}{\partial w_s^p} = \left\{ -\beta_{ss} + \frac{\beta_{sk}\beta_{ks}}{\beta_{kk}} \sum_{i=0}^{n} (1-\lambda^s)^i \lambda^s \right\} \overline{w}_s^p \Big/ \overline{S}$$

where λ^s is the capital adjustment parameter for sawmills and $i = 1 \ldots n$ are the number of years in the intermediate adjustment period (usually 2 or more years). LR elasticities are calculated when λ^s is set equal to one, as this is when the long run demand for capital is equal to the optimal capital stock.

The endogenous variables on the right hand side of the equations require using an instrumental variable method to estimate the parameters. The endogenous variables in the system are stumpage price, stumpage quantity, and capital stock. The rest of the variables in the system are used as the instrument variables. In this case, the non-linear three-stage least squares (NL3SLS) method is preferred over the seemingly unrelated regression (SUR) method for estimating the model, as it is a consistent estimator when the first difference of the capital stock and the error term are not independent (Greene 2003). This dependency condition is confirmed using a Hausman (1978) test.

Results

The results of the lagged adjustment model are shown in table 3. The negative sign for the PNW-Westside sawlog stumpage price meets economic theory of a downward sloping demand curve, and the positive signs on the other inputs suggest that labor and capital are substitutes for stumpage as factors of the production process. The large value for the lagged quantity parameter (0.66) indicates relatively slow adjustment. The positive signs for stumpage price and inventory both match the theory that as prices and inventories increase, so does supply. A large estimate for *D89* (-820.4) accounts for the large shift in supply due to harvest restrictions and other changes in the industry.

Results for the PNW-Eastside demand equation are all significant at the 90 percent confidence level with the exception for the price of lumber and the constant. Stumpage price is negative and significant. The signs on the other inputs show that labor and capital are both substitutes for stumpage in the production of sawnwood. Firms are also slow to adjust their factors of production. For the eastside's supply equation, stumpage price was positive, indicating an upward sloping supply curve that fits economic theory. Again, a large estimate for *D89* (-184.7) accounts for a large shift in sawtimber supply since the late 1980s, although the absolute decline in stumpage quantity is not as large as the westside because the region has smaller total production.

The South sawlog parameter estimates for the lagged adjustment model were all significant at the 90 percent level. Stumpage price was negative, and the signs on the other inputs indicate that capital and labor are substitutes for stumpage. The estimated the speed of adjustment is similar to the PNW. The variables for the South's sawlog supply equation were all significant at the 90 percent level or better, and sawlog stumpage price and inventory parameters were positive, indicating that the supply function was correctly specified. The pulplog stumpage price parameter estimate that was included in the supply function was positive and significant, revealing that sawlogs and pulplogs are complements. Many firms sell pulpwood as a byproduct of a softwood harvest, so that sawlogs and pulplogs are net complements in production.

The pulplog parameter estimates for the Southern regression in the lagged adjustment model were significant at the 90 percent level, with the exception of wage. The pulpwood stumpage price parameter was negative, and the lower value for the lagged quantity parameter (0.52) suggests that Southern pulpwood processing mills have a faster adjustment rate than regional sawmills. The pulplog stumpage price was positive as was the sawlog stumpage price parameter, reaffirming that sawlogs and pulplogs are net complements in production.

Results for Dynamic Capital Adjustment Model

The results of the dynamic capital adjustment model are shown in table 4. Most of the parameters in the regional supply and demand equations have the same sign and magnitudes as the lagged adjustment models, though many estimates had a reduction in explanatory power relative to the simple model. Many of the parameter estimates for the capital adjustment equations were also not significant. As expected, capital and labor are found to be substitutes for stumpage in the production process. The only exception is that the parameter on labor price is insignificant in the South sawlog demand model. Labor and capital are also found to be substitutes for pulpwood stumpage in the South.

The capital adjustment parameter (λ) is positive and significant at least at the 10% level in all regions except the PNW-East. For the PNW-West, the parameter is 0.20, implying that capital turns over about once every 8 years in that region. The coefficient for the PNW-East is 0.05, but insignificant, suggesting that capital takes many years to adjust in that region, and that investments potentially lag relative to the rest of the economy. The capital adjustment coefficient for the South's sawtimber industry is approximately 0.14, which is comparable to the Pacific Northwest estimates. This indicates that eighty percent of the change to the desired level of capital stock is accomplished over a 10 year period. The capital adjustment parameter for the South's pulp and paper industry is 0.33, suggesting that there is substantially faster capital adjustment than the sawtimber processing sector, as was also determined in the lagged adjustment model.

These results are consistent with a national dynamic demand model for major sectors in U.S. manufacturing developed by Berndt, Fuss, and Waverman (1980). They estimated a partial adjustment parameter of 0.12 for all wood products, and 0.42 for pulp and paper products. The difference between sawmill and pulp and paper mills estimates may be explained by the structure of the production process for both industries. Pulp and paper mills tend to be larger in size and capacity, thereby allowing more possibilities to invest not only in new machinery but also to improve upon older machines to improve efficiency and capacity (Ince et al., 2001). Sawmills tend to be smaller in nature and are often dependent on the size and species of the available timber in a given region, thereby limiting the ability to quickly adjust to changing market conditions.

Elasticity Estimates

In general the own-price elasticity estimates suggest relatively inelastic demand for timber in the short run, and that all regions respond similarly to a change in stumpage price, even without observing the same structural change or species of input. For the PNW-Westside, SR elasticity estimates are -0.18 to -0.25, which are at the high end of earlier estimates from Merrifield and Singleton (1986) and Haynes, Connaughton, and Adams (1981). For the PNW-Eastside, SR elasticity ranges from -0.002 to -0.08. These suggest fairly low elasticity in the SR, but are in-line with the earlier estimates (see table 1). For the South sawtimber market, the SR own price elasticity ranges from -0.12 to -0.20, and for the pulp market, -0.07 to -0.15. These are both lower than the results found in Carter (1992) and Newman (1987). These earlier models of the southern timber markets did not account for capital adjustments, as modeled here, and therefore may have captured some long run effects in their static models, pushing up the elasticity estimates.

The LR elasticity estimates are higher in both the lagged adjustment and dynamic factor demand models, and supports the hypothesis of Le Chatelier's principle. The dynamic factor demand model also provides a method to capture an intermediate run (IR) elasticity estimate, which is assumed to be three years for all regions. For the PNW-Westside, we find that there is little change in the elasticity estimate from the SR to the IR. Most of the change in elasticity occurs from the IR to the LR. Similar results are found for the other regions. LR elasticities for the region are in the range of -0.35 to -0.48. While still inelastic, this suggests that factor demand becomes more elastic in the LR. This result can help explain the relatively quick reduction in real prices in responses to the supply shocks of the early 1990's. For example, for the PNW-Westside, a permanent 30% reduction in supply, such as occurred in the early 1990's, would be expected to increase prices by 120% in the first year or two. However, over a 5-10 year period, one would expect this price increase to moderate to only an 85% increase in prices. While still large, the smaller price effect could have important welfare consequences. LR elasticity estimates are similar for the PNW-Eastside, indicating that markets will react to harvest restrictions in a similar fashion.

The South's pulpwood demand models produced very inelastic SR elasticities that are on the low end of estimates from other pulpwood stumpage demand studies (Carter 1992; Newman 1987). No other econometric model focusing on regional U.S. pulplog supply and demand has attempted to distinguish between SR and LR elasticities. These results, coupled with the large capital adjustment parameter estimated for the southern pulpwood market, indicate that the production process is relatively consistent and that perhaps the faster turnover of capital is able to account for this.

Wage is relatively elastic in the LR for both regions in the PNW, and it can fluctuate more in this region than in the South. Using the earlier example where harvests in the PNW were reduced significantly in the 1990s, we would expect to see a similar level of decline in wages in the region over the same time period, resulting in significant losses for workers in the timber processing industry. On the contrary, an increase in production in the South is not expected to increase wages for that region by the same magnitude, even over the long run. High elasticity estimates for the South's dynamic capital adjustment models suggest that fluctuations in capital are expected to occur at a greater magnitude than the region's labor force, regardless of whether one is employed in the pulp and paper or sawmill industry.

The SR stumpage own-price elasticities of supply for sawlogs are inelastic for all three regions (ranges from 0.073 to 0.258). These estimates are towards the low end of previous studies (see table 1), and suggest that landowners are not very responsive to fluctuating prices, and perhaps harvest on a more fixed agenda than when previous estimates were derived in the 1980s. The pulplog stumpage supply elasticities for the South (0.487 and 0.598) were greater than the region's sawlog estimates, revealing that landowners who produce pulplogs respond to short-term changes in market variables more than sawlog producers.

Welfare Effects

Welfare changes from a supply shock vary with the specification of the supply and demand curves. An example of how differences between SR and LR elasticity estimates can have a large impact on welfare calculations for a given reduction in quantity is shown in figure 1. Not shown in the graph is the series of intermediate run demand curves, which have slopes that range between the short run (D_{SR}) and long run (D_{LR}) demand. The dynamic welfare change calculations assume that the demand curve rotates from D_{SR} to D_{LR} while the original equilibrium point (Q*, P*) is held constant. The time that it takes firms to adjust to the LR is determined by the dynamic capital adjustment parameter (λ). Apparent in the graph is that the supply curve must shift farther back along the D_{SR} relative to D_{LR} demand curve for the change in quantity to remain constant. This leads to significantly larger changes in welfare relative to the LR scenario, as highlighted by the light gray areas. Welfare changes calculated along the path of demand and supply shifts fall somewhere in between the two extremes.

Forest landowners and lumber and wood producers in the Pacific Northwest all faced significant losses over the course of the 1990s due to changes in the structure of the region's timber industry, while those in the South benefited from an increase in market share. Averages of the estimated supply and demand elasticities from the dynamic capital adjustment model were used to calculate regional changes in welfare using an equilibrium displacement model (see, for example, Davis and Espinoza 1998; Sun and Kinnucan 2001). Status quo (pre-harvest reduction) equilibrium prices and quantities are assumed to be the average price and quantity for regional stumpage from 1980-1988, when the market was relatively stable. The SR demand curve welfare change calculations assume a constant estimated elasticity for the duration of the supply shifts from 1989-2001 using average estimates of the two models shown in table 5. The dynamic demand curve assumes that the elasticity of demand changes from the SR to the LR over time using the estimated capital adjustment parameter (λ) from the dynamic capital adjustment model, and is estimated to be at least 10 years for all three timber supply regions. The regional supply curve is assumed to have a constant elasticity of for all scenarios, and is also an average of the two estimates.

Changes in welfare associated with the federal timber harvest restrictions are calculated by differencing the actual stumpage quantities from the status quo average (P*, Q*), beginning in 1989. This procedure is then used to estimate the annual shifts in the regional supply curve relative to a hypothetical case where there were no harvest restrictions. A summary of the estimated changes in regional consumer, producer, and total surplus for the three timber supply regions is shown in table 6. The results are listed as a discounted sum of annual changes in stumpage supply from 1989 to 2001. The welfare calculations represent the present value in 1989, and assume an annual discount rate of 0.05, thus giving more weight to the supply shifts in the earlier years of adjustment. The total change in welfare is simply a summation of the three major softwood supply regions.

The calculations find that harvest reductions in the entire Pacific Northwest resulted in present value total surplus losses in the two regions' sawlog market of $1.7 to $1.9 billion, depending on the different elasticity and dynamic adjustment assumptions. Large losses experienced in the PNW were not offset by welfare improvements in the South, as the total welfare change for the three major timber supply regions ranges from -$0.7 to -$1.1 billion. Consumer losses in the PNW are 40-48% less, and producer losses are 40-76% larger, if estimated with a dynamic demand curve instead of the standard short run response. The relatively larger effects on producers make sense intuitively since the less elastic side of the market will bear the greater incidence of a change in price. For the three regions combined, the long-run, dynamic estimates suggest a 37% smaller welfare effect than the short-run model. Thus, estimating and using highly inelastic demand functions to measure welfare effects over a given time period could substantially overstate the welfare effects.

Discussion and Conclusions

This paper estimates two derived demand systems for softwood stumpage in three major softwood timber supply regions. This analysis uses one of the most comprehensive datasets in timber and wood product demand estimation, spanning from 1950 to 2001. The methodology and elasticity estimations discussed in this paper are a pivotal step towards obtaining a sound understanding of how the derived factors of demand in timber markets evolve and can vary over time regions, and with the specification of the model. Estimates derived in this paper can give researchers and policy makers more insight on how timber markets react to various shocks over time, and help produce more efficient timber production forecasts and the resulting welfare effects.

Results indicate that there are differences between SR and LR demand elasticities for all timber supply regions, and these estimates can vary with the structure of the model and regional production process. As expected, the price elasticity of demand for stumpage increases over time, thereby satisfying the Le Chatelier principle. Elasticity estimates for other inputs also are shown to become more elastic over time, indicating that there is flexibility between the three factors of demand (stumpage, labor, capital) when producers have adequate time to adjust. While the capital adjustment period is found to be a decade or more for sawtimber markets in all regions, the adjustment period in the South's pulpwood market appears to be a shorter 5 years. Differences in capital adjustment paths can be explained by the size and capacity of the pulp and paper mills that often have economies of scale and have the capabilities to upgrade existing machines and improve efficiency. Using a simple static demand model ignores this adjustment process and consequently overstates the welfare effects.

Neither the lagged adjustment model nor the two dynamic factor demand models consistently estimated larger degrees of changes between short run and long run elasticities. The key contribution of the dynamic model over the lagged adjustment model is its ability to determine the time and path that capital stock adjusts by estimating an explicit capital adjustment parameter. This has important policy implications, as some have called for the need to evaluate how quickly capital investments in timber growing and manufacturing may adapt to future regional changes in forest resources (Irland et al. 2001). These slow adjustment rates imply that the adoption of technology embodied in new capital inputs will take longer in the timber processing industry relative to other sectors of the economy. Investment-oriented policies, such as investment tax credits, are likely to have a limited effect on growth in the industry.

Acknowledging the difference between the SR and LR own-price elasticities of demand has important policy implications. First, many timber supply models used to forecast changes in the market assume that a single price elasticity estimate holds for all periods (e.g., Adams and Haynes 1996). Second, this measurement is often obtained using sample means of an outdated econometric model that does not include the structural change that has occurred in recent years (Brown and Zhang 2005). These misspecifications can have significant effects, especially in the case where the model is investigating potential long run welfare changes associated with a given shock (Sun 2006). If the demand curve is assumed to be highly inelastic (as in the case of most of our SR estimates), then price changes will affect total welfare differently depending on the elasticity of the supply curve (which we found here to be price inelastic). As shown in this paper, however, firms adjust in the long run to a shock by changing their inputs and production process (or even shutting down). As firms adjust their share of inputs over time, the slope of the derived demand curve will change. Welfare measures based solely on short run estimates of demand will overstate consumer losses and understate producer gains. Our analysis finds that this overstatement could be significant. For the example of the late 1980s reduction in federal timber harvests in the western U.S., using short-run demand curves to estimate welfare effects would cause would overstate net welfare effects by as much as $400 million in present value terms, or 37%.

References

Adams, D., and R.W. Haynes. 1980. "The 1980 softwood timber assessment market model: structure, projections, and policy simulations." *Forest Science Monograph 22*: 1-64.

---. 1996. *The 1993 Timber Assessment Market Model: Structure, Projections and Policy Simulations.* Gen. Tech. Rep. PNW-GTR-368. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Adams, D., K.C. Jackson, and R.W. Haynes. 1988. *Production, Consumption, and Prices of Softwood Products in North America – Regional Time Series Data, 1950-1985*. Resour. Bull. PNW-RB-151. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Adams, D., R.W. Haynes, and A.J. Daigneault. 2006. *Estimated Timber Harvest by U.S. Region and Ownership, 1950-2002*. Gen. Tech. Rep. PNW-GTR-659. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Bartelsman, E.J., R.A. Becker, and W.B. Gray. 2000. *NBER-CES Manufacturing Industry Database*. Last accessed May 25, 2006: http://www.nber.org/nberces/.

Berndt, E.R., M.A. Fuss, and L. Waverman. 1980. *Dynamic adjustment models of industrial energy demand: empirical analysis for U.S. Manufacturing, 1947-1974*. Electric Power Research Institute, Res Rep EA-1613, Palo Alto, CA.

---. 1977. *Dynamic models of the industrial demand for energy*. Electric Power Research Institute, Res Rep EA-580, Palo Alto, CA.

Berndt, E.R., and B.C. Field, eds. 1981. *Modeling and Measuring Natural Resource Substitution.* Cambridge, MA: MIT Press.

Bohi, D.R. 1981. *Analyzing Demand Behavior: A Study of Energy Elasticites*. Baltimore, MD: Resources For the Future, by The Johns Hopkins University Press.

Brown, R., and D. Zhang. 2005. "The sustainable forestry initiative's impact on stumpage markets in the U.S. South." *Canadian Journal of Forest Research*. 35:2056-2064.

Carter, D.R. 1999. "Structural change in Southern softwood stumpage markets." In: K.L. Abt and R.C. Abt, eds. *Proceedings of the 1998 Southern Forest Economics Workshop*. Southern Research Station, USDA Forest Service, Williamsburg, VA. pp. 112-117.

Davis, G.C., and M.C. Espinoza. 1998. “A unified approach to sensitivity analysis in equilibrium displacement models.” *American Journal of Agricultural Economics* 80:868-879.

Greene, W.H. 2003. *Econometric Analysis: Fifth Edition*. Upper Saddle River, NJ: Prentice Hall.

Haynes, R.W. 2006. “Will markets provide sufficient incentive for sustainable forest management?” In R.L Deal, and S.M. White, eds. *Understanding Key Issues of Sustainable Wood Production in the Pacific Northwest.* Gen. Tech. Rep. PNW-GTR-626. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, pp. 13-19.

Haynes, R.W., K.P. Connaughton, and D.M. Adams. 1981. *Projections of the Demand for National Forest Stumpage, by Region, 1980-2030.* USDA Forest Service Research Paper PNW-282. Portland, OR: U.S. Dept. of Agriculture, Forest Service, Pacific Northwest Forest and Range Exp. Station.

Haynes, R.W., tech, coord. 2003. *An analysis of the timber situation in the United States: 1952 to 2050*. Gen. Tech. Rep. PNW-GTR-560. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Houthakker, H.S., and L.D. Taylor. 1970. *Consumer Demand in the United States: Analyses and Projections*. Cambridge, MA: Harvard University Press.

Howard, J.L. 2003. *U.S. Timber Production, Trade, Consumption, and Price Statistics*, 1965-2002. Res. Pap. FPL-RP-615. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Ince, P.J., X. Li, M. Zhou, J. Buongiorno, and M.R. Reuter. 2001. *United States Paper, Paperboard, and Market Pulp Capacity Trends by Process and Location, 1970–2000*. Res. Pap. FPL-RP-602. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Irland, L.C., D.Adams, R. Alig, C. J. Betz, C. Chen, M. Hutchins, B.A. McCarl, K. Skog, and B.L. Sohngen. 2001. “Assessing socioeconomic impacts of climate change on U.S. forests, wood-product markets, and forest recreation.” *BioScience* 51(9):753-764.

Koyck, L.M. 1954. *Distributed Lags and Investment Analysis*. Amsterdam: North-Holland Publishing Company.

Krichene, N. 2002. “World crude oil and natural gas: a demand and supply model.” *Energy Economics* 24:557-576.

Lucas, R. 1967. “Optimal investment policy and the flexible accelerator.” *International Economic Review* 8(1):78-85.

Merrifield, D.E., and W.R. Singleton. 1986. "A dynamic cost and factor demand analysis for the Pacific Northwest lumber and plywood industries." *Forest Science* 32(1):220-233.

Murray, B.W., and D.N. Wear. 1998. "Federal timber restrictions and interregional arbitrage in U.S. lumber." *Land Economics* 74(1):111-128.

Newman, D.H. 1987. "An econometric analysis of the southern softwood stumpage market: 1950-1980." *Forest Science* 33(4):932-945.

Robinson, V.L. 1974. "An econometric model of softwood lumber and stumpage markets, 1947-1967." *Forest Science* 20:171-179.

Samuelson, P.A. 1947. *Foundations of Economic Analysis*. Cambridge, MA: Harvard University Press.

Smith, B.W., P.D. Miles, J.S. Vissage, and S.A. Pugh. 2004. *Forest Resources of the United States, 2002: A Technical Document Supporting the USDA Forest Service 2005 Update of the RPA Assessment*. Gen. Tech. Rep. GTR-NC-241. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station.

Stevens, J.A. 1995. "Heterogeneous labor demand in the Western Washington sawmill industry." *Forest Science* 41(1): 181-193.

Sun, C. 2006. Welfare effects of forestry best management practices in the United States. *Canadian Journal of Forest Research* 36:1674-1683.

Sun, C., and H.W. Kinnucan. 2001. "Economic impact of environmental regulations on southern softwood stumpage markets: A reappraisal." *Southern Journal of Applied Forestry* 25(3):108-115.

Treadway, A.B . 1974. "The globally optimal flexible accelerator." *Journal of Economic Theory* 7:17-39.

---. 1971. "The rational multivariate flexible accelerator." *Econometrica*. 39(5): 845-855.

Wear, D. W., and B.C. Murray. 2004. "Federal timber restrictions, interregional spillovers, and the impact on US softwood markets." *Journal of Environmental Economics and Management* 47:307-330.

U.S. Bureau of Labor Statistics. 2005. Website for interactive query of manufacturing costs. Last accessed December 10, 2005: http://www.bls.gov/data/home.htm.

U.S. Council of Economic Advisors. 2005. *Economic Report of the President*. Washington D.C.

U.S. Department of Commerce, Bureau of the Census. 1950-2004. *Annual Survey of Manufacturers*. Washington D.C.

---. 1950-2004. *Census of Manufacturers*. Washington D.C.

Table 1. Summary of Econometric Studies of Softwood Stumpage Demand and Supply Elasticities

Study	Region	Product	SR Demand	LR Demand	SR Supply
Robinson (1974)	South	Softwood	-0.52		
Adams and Haynes (1980)	SC	Softwood			0.39 - 0.47
Adams and Haynes (1980)	SE	Softwood			0.30 - 0.47
Haynes et al (1981)	SC	Softwood	-0.13		
Haynes et al (1981)	SE	Softwood	-0.05		
Adams and Haynes (1985)	SC	Softwood			0.17 - 0.63
Adams and Haynes (1985)	SE	Softwood			0.17 - 1.20
Daniels and Hyde (1986)	N. Carolina	Hard and Soft	-0.03		0.27
Newman (1987)	South	Pulpwood	-0.43		0.23
Newman (1987)	South	Sawtimber	-0.57		0.55
Abt (1987)	South	Lumber	-0.25		
Robinson and Fey (1990)	South	Softwood	-0.25		
Abt and Kelly (1991)	FL and GA	Softwood	-0.10		0.30 - 0.40
Carter (1992)	Texas	Pulpwood	-0.41		0.28
Newman and Wear (1993)	SE	Sawtimber			0.22 - 0.27
Newman and Wear (1993)	SE	Pulpwood			0.33 - 0.58
Adams and Haynes (1996)	SC	Softwood			0.06 - 0.26
Adams and Haynes (1996)	SE	Softwood			0.16 - 0.18
Carter (1999)	South	Sawtimber			0.15 - 0.35
Carter (1999)	South	Pulpwood			0.17 - 0.27
Polyakov et al. (2004)	Alabama	Pulpwood	-1.72		0.35
Adams and Haynes (1980)	PNW-West	Softwood			0.29 - 0.32
Adams and Haynes (1980)	PNW-East	Softwood			0.19 - 0.29
Haynes et al (1981)	PNW-West	Softwood	-0.14		
Haynes et al (1981)	PNW-East	Softwood	-0.17		
Merrifield and Haynes (1985)	PNW-West	Lumber	-0.001		
Merrifield and Haynes (1985)	PNW-West	Plywood	0.02		
Merrifield and Haynes (1985)	PNW-East	Lumber	-0.07		
Merrifield and Haynes (1985)	PNW-East	Plywood	-0.85		
Merrifield and Singleton (1986)	PNW	Lumber	-0.01	-0.023	
Merrifield and Singleton (1986)	PNW	Plywood	-0.10	-0.105	
Abt (1987)	West	Lumber	-0.20		
Stevens (1995)	West. WA	Sawtimber	-0.18	-0.47	0.42 - 0.44
Adams and Haynes (1996)	PNW-West	Softwood			0.42 - 0.44
Adams and Haynes (1996)	PNW-East	Softwood			0.17 - 0.40

SE = South East, SC = South Central, PNW = Pacific Northwest

Table 2. Variables Used in the Estimation of Factor Demand Models

Variables	*Symbol*	*Description*	*Source*
Softwood sawlog supply/demand	S^s	Annual supply/demand of sawlogs (million ft3), 1950-2002	Adams et al. (2006), Table 6
Softwood pulpwood supply/demand	S^p	Annual supply/demand of pulpwood (million ft3), 1950-2002	Adams et al. (2006), Table 6
Price of sawlog stumpage	p^s, w_s^s	Average annual price of sawlogs ($/MBF)	Howard (2003), Table 26 Warren (2004), Table 102
Price of pulplog stumpage	p^p, w_p^p	Average annual price of pulplogs ($/cord)	Howard (2003), Table 26
Labor costs in logging industry	w_l^f	Wage rate of workers in logging industry ($/hour)	Howard (2003), Table 3
Standing inventory	k^f	Total inventory of softwood timber on regional timberland (million ft3)	Haynes (2003), Tables 34, 36, 42, 44 Smith et al. (2004), Table 30
1989 Dummy	*D89*	Dummy equal to one if year is 1989 or later, 0 otherwise	Years of federal timber harvest restrictions in Pacific Northwest
Price of lumber	P^s	Price of regional softwood lumber ($/MBF)	Howard (2003), Tables 35, 36
Price of final product pulp	P^p	Price of regional softwood pulp ($/cord)	Howard (2003), Table 51
Labor costs in sawmill industry	w_l^s	Wage rate of workers in sawmill industry ($/hour)	Howard (2003), Table 3
Labor costs in pulp and paper industry	w_l^p	Wage rate of workers in pulp and paper industry ($/hour)	Howard (2003), Table 3
Capital Stock in sawmill industry	k^s	Value of sawmill machines and buildings (billion $)	U.S. Bureau of Labor Statistics (2005) Bartlesman et al. (2000)
Capital Stock in pulp and paper industry	k^p	Value of pulp and paper mill machines and buildings (billion $)	U.S. Bureau of Labor Statistics (2005) Bartlesman et al. (2000)
User cost of capital	u_t^s, u_t^p	Function of the cap. invest. ppi, general ppi, dep. rate and the interest rate	U.S. Bureau of Labor Statistics (2005) Bartlesman et al. (2000)
Depreciation rate	δ	Constant depreciation of capital stock in sawmill and pulp and paper industry	Economic Report of the President (2004)
Real interest rate	*r*	Yield on AAA bonds	Economic Report of the President (2004)

Table 3. Parameter Estimates for Regional Softwood Stumpage Demand System, Lagged Adjustment Model

PACIFIC NORTHWEST - WESTSIDE

SAWLOG SUPPLY				SAWLOG DEMAND			
Parms	Variable	Estimate		Parms	Variable	Estimate	
α0	Constant	-1019.0		β0	Constant	-214.1	
α1	Stump Saw Price	3.779	**	β1	Stumpage Price	-2.663	***
α2	Priv. Merch. Inv.	0.027	*	β2	Lumber Price	0.745	*
α3	Logging Wage	148.3	***	β3	Sawmill Wage	93.40	***
α4	1989 Dummy	-820.4	***	β4	Capital	81.32	
				β5	Lag Quantity	0.658	***

PACIFIC NORTHWEST - EASTSIDE

SAWLOG SUPPLY				SAWLOG DEMAND			
Parms	Variable	Estimate		Parms	Variable	Estimate	
α0	Constant	62.6		β0	Constant	-249.2	
α1	Stump Saw Price	1.134	*	β1	Stumpage Price	-0.473	*
α2	Total Merch. Inv.	0.006		β2	Lumber Price	0.329	
α3	Logging Wage	21.42	***	β3	Sawmill Wage	16.88	***
α4	1989 Dummy	-184.7	***	β4	Capital	382.2	***
				β5	Lag Quantity	0.671	***

SOUTH

SAW SUPPLY				SAW DEMAND			
Parms	Variable	Estimate		Parms	Variable	Estimate	
α0	Constant	598.9	**	β0	Constant	-806.9	***
α1	Stump Saw Price	2.708	*	β1	Stumpage Price	-2.240	**
α2	Priv. Merch. Inv.	0.061	***	β2	Lumber Price	5.283	***
α3	Logging Wage	-213.0	***	β3	Sawmill Wage	76.92	***
α4	Stump Pulp Price	46.92	***	β4	Capital	69.11	**
				β5	Lag Quantity	0.729	***

SOUTH

PULP SUPPLY				PULP DEMAND			
Parms	Variable	Estimate		Parms	Variable	Estimate	
δ0	Constant	-1461.1	***	φ0	Constant	-247.2	*
δ1	Stump Pulp Price	64.88	***	φ1	Stumpage Pulp Price	-8.60	*
δ2	Total Private Inv.	0.0268	***	φ2	Pulp Price	10.49	***
δ3	Logging Wage	5.031		φ3	Pulpmill Wage	27.82	**
δ4	Stump Saw Price	1.8734	**	φ4	Capital	71.87	***
				φ5	Lag Quantity	0.519	***

estimation using 3SLS, with exogenous variables as instruments

*** significant at 1% level

** significant at 5% level

* significant at 10% level

Table 4. Parameter Estimates for Regional Softwood Stumpage Demand System, Dynamic Capital Adjustment Model

PACIFIC NORTHWEST - WESTSIDE								
SAWLOG SUPPLY			**SAWLOG DEMAND**			**SAW CAP. ADJUST.**		
Parms	**Variable**	**Estimate**	**Parms**	**Variable**	**Estimate**	**Parms**	**Variable**	**Estimate**
α_s	Constant	284.2 *	β_s	Constant	-35.97	β_{kk}	Constant	0.1029 *
α_{ss}	Stump Saw Price	2.448	β_{ss}	Stumpage Price	-3.719 ***	β_k	Constant	0.1366 **
α_{sk}	Priv. Merch. Inv.	0.010 ***	β_{sP}	Lumber Price	1.395 *	β_{kP}	Lumber Price	0.0038 *
α_{sl}	Logging Wage	112.7 ***	β_{sl}	Sawmill Wage	219.3 ***	β_{ks}	Stumpage Price	0.0009 ***
α_{s89}	1989 Dummy	-823.1	β_{sk}	Capital	172.4 *	β_{kl}	Sawmill Wage	-0.0114 ***
			β_{sGDP}	GDP	-0.021	λ^s	Cap. Adjust.	0.2034 ***
PACIFIC NORTHWEST - EASTSIDE								
SAWLOG SUPPLY			**SAWLOG DEMAND**			**SAW CAP. ADJUST.**		
Parms	**Variable**	**Estimate**	**Parms**	**Variable**	**Estimate**	**Parms**	**Variable**	**Estimate**
α_s	Constant	142.6	β_s	Constant	228.8	β_{kk}	Constant	-0.1006
α_{ss}	Stump Saw Price	0.437	β_{ss}	Stumpage Price	-0.009	β_k	Constant	-0.0213
α_{sk}	Total Merch. Inv.	0.004	β_{sP}	Lumber Price	-0.522	β_{kP}	Lumber Price	-0.0005
α_{sl}	Logging Wage	25.2 ***	β_{sl}	Sawmill Wage	69.85 ***	β_{ks}	Stumpage Price	-0.0033
α_{s89}	1989 Dummy	-148.2 ***	β_{sk}	Capital	93.46	β_{kl}	Sawmill Wage	0.0252
			β_{sGDP}	GDP	-0.019 **	λ^s	Cap. Adjust.	0.0548
SOUTH								
SAW SUPPLY			**SAW DEMAND**			**SAW CAP. ADJUST.**		
Parms	**Variable**	**Estimate**	**Parms**	**Variable**	**Estimate**	**Parms**	**Variable**	**Estimate**
α_s	Constant	293.7	β_s	Constant	145.2	β_{kk}	Constant	0.0877 **
α_{ss}	Stump Saw Price	1.675	β_{ss}	Stump Saw Price	-3.665 *	β_k	Constant	0.2058
α_{sk}	Priv. Merch. Inv.	0.054	β_{sP}	Lumber Price	5.896	β_{kP}	Lumber Price	0.0003
α_{sl}	Logging Wage	-140.9 ***	β_{sl}	Sawmill Wage	-15.21	β_{ks}	Stumpage Price	-0.0019
α_{sp}	Stump Pulp Price	53.2 ***	β_{sk}	Capital	255.4	β_{kl}	Sawmill Wage	-0.0128
			β_{sGDP}	GDP	0.060 **	λ^s	Cap. Adjust.	0.1413 *
SOUTH								
PULP SUPPLY			**PULP DEMAND**			**PULP CAP. ADJUST.**		
Parms	**Variable**	**Estimate**	**Parms**	**Variable**	**Estimate**	**Parms**	**Variable**	**Estimate**
δ_p	Constant	-1654.9 ***	φ_p	Constant	262.7	φ_{kk}	Constant	0.0358 *
δ_{pp}	Stump Pulp Price	79.6 ***	φ_{pp}	Stump Pulp Price	-19.25 *	φ_k	Constant	0.2410 ***
δ_{pk}	Total Private Inv.	0.025 ***	φ_{pP}	Pulp Price	12.583 ***	φ_{kP}	Pulp Price	0.0050
δ_{pl}	Logging Wage	29.04	φ_{pl}	Pulpmill Wage	6.708	φ_{kp}	Stump Pulp Price	-0.0089 ***
δ_{ps}	Stump Saw Price	1.004	φ_{pk}	Capital	159.54 ***	φ_{kl}	Pulpmill Wage	-0.0077
			φ_{GDP}	GDP	0.0456 ***	λ^p	Cap. Adjust.	0.3255 *

estimation using NL3SLS, with exogenous variables as instruments

*** significant at 1% level

** significant at 5% level

* significant at 10% level

Table 5. Estimated Supply and Demand Elasticities for Three Timber Supply Regions

		Lagged Adjustment		Dynamic Capital Adjustment		
	Variable	**SR**	**LR**	**SR**	**IR[a]**	**LR**
PNW-W Sawlog Demand	*Stumpage Price*	-0.181	-0.483	-0.253	-0.273	-0.351
	Lumber Price	0.098	0.260	0.183	0.354	1.023
	Sawmill Wage	0.441	1.174	1.036	1.054	1.126
	Capital Stock	0.093	0.246	0.000	0.829	1.907
PNW-W Sawlog Supply	*Stump Saw Price*	0.258		0.167		
	Logging Wage	0.724		0.550		
	Priv. Merch. Inv	0.652		0.242		
PNW-E Sawlog Demand	*Stump Saw Price*	-0.079	-0.240	-0.002	-0.029	-0.506
	Lumber Price	0.189	0.574	-0.299	-0.313	-0.540
	Sawmill Wage	0.311	0.945	1.286	1.310	1.717
	Capital Stock	0.415	1.263	0.000	0.439	1.010
PNW-E Sawlog Supply	*Stump Saw Price*	0.189		0.073		
	Logging Wage	0.409		0.228		
	Total Merch. Inv	0.368		0.480		
South Sawlog Demand	*Stump Saw Price*	-0.120	-0.443	-0.197	-0.239	-0.497
	Lumber Price	0.441	1.623	0.492	0.501	0.556
	Sawmill Wage	0.219	0.805	-0.043	-0.058	-0.149
	Capital Stock	0.080	0.295	0.000	1.355	3.117
South Sawlog Supply	*Stump Saw Price*	0.145		0.090		
	Logging Wage	-0.864		-0.572		
	Priv. Merch. Inv	1.168		1.031		
	Stump Pulp Price	0.286		0.325		
South Pulplog Demand	*Stump Pulp Price*	-0.065	-0.134	-0.145	-0.242	-0.443
	Pulp Price	0.241	0.887	0.289	0.453	0.794
	Pulpmill Wage	0.176	0.647	0.042	0.113	0.259
	Capital Stock	0.140	0.515	0.000	3.673	8.450
South Pulplog Supply	*Stump Pulp Price*	0.487		0.598		
	Logging Wage	0.025		0.145		
	Total Merch Inv	0.690		0.647		
	Stump Saw Price	0.124		0.066		

a. Intermediate run (IR) is three years for all regions and outputs

Table 6. Present Value of Estimated Annual Welfare Changes from Federal Harvest Restrictions, 1989-2001, Under Different Elasticity Assumptions (r=0.05)

		Short Run	Dynamic	Difference in Estimates
		million $		*%*
PNW-W	**PV Δ CS**	$ (1,023)	$ (617)	-39.6%
PNW-W	**PV Δ PS**	$ (682)	$ (953)	39.7%
PNW-W	**PV Δ TS**	$ (1,704)	$ (1,570)	-7.9%
PNW-E	**PV Δ CS**	$ (226)	$ (117)	-48.3%
PNW-E	**PV Δ PS**	$ (129)	$ (227)	76.4%
PNW-E	**PV Δ TS**	$ (355)	$ (344)	-3.0%
South	**PV Δ CS**	$ 411	$ 332	-19.2%
South	**PV Δ PS**	$ 547	$ 887	62.0%
South	**PV Δ TS**	$ 958	$ 1,219	27.2%
Total	**PV Δ CS**	$ (838)	$ (402)	-52.0%
Total	**PV Δ PS**	$ (263)	$ (293)	11.4%
Total	**PV Δ TS**	$ (1,101)	$ (695)	-36.8%

CS = consumer surplus, PS = producer surplus, TS = total surplus
present value (PV) discounted to 1989, with a discount rate of 0.05

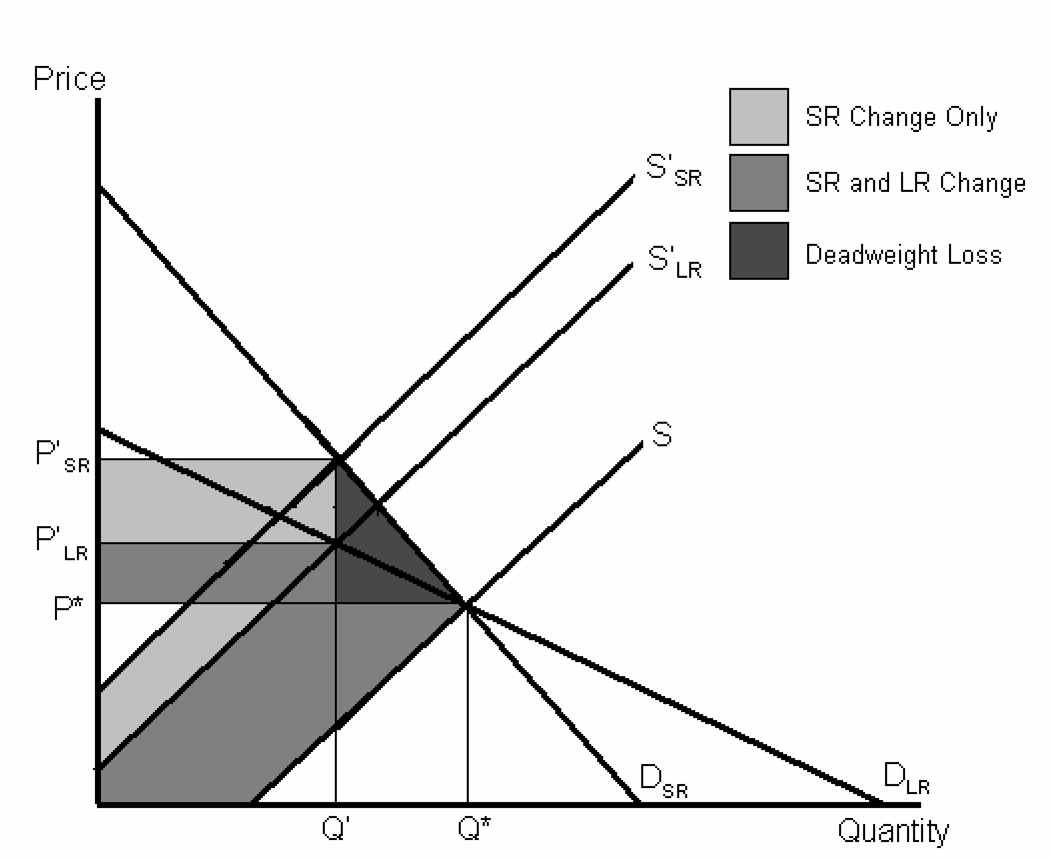

Figure 1. Welfare changes with short run and long run demand specifications