AN ASSESSMENT OF FOUR LARGE SCALE TIMBER MARKET MODELS

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ABSTRACT

Differences in timber market models that arise from alternative assumptions and fundamental differences in theory and structure can lead to disparate published results, as well as confusion among policy analysts and industry. This paper presents a thorough comparison of four widely used models, and then analyzes a set of published market predictions relative to historical data. The goal is to understand how fundamental differences between the models may affect market predictions. Several conclusions are drawn. First, market outlooks are largely a function of exogenous demand growth and timberland management assumptions, although differences in theory and structure are important. Second, spatial equilibrium models adapt to changing conditions by shifting price growth from region to region, while dynamic optimization models shift harvest quantities. Finally, model output must be assessed carefully, and often with a thorough understanding of input assumptions and alternative scenarios.

KEYWORDS: Forest Sector Models, Timber Markets, Policy Analysis, Market Outlooks

JEL CLASSIFICATION: C62, Q21, Q23

INTRODUCTION

Forest economists long have developed and used timber market models for policy analysis, price and harvest projections, and other questions related to the future of the forest sector. Traditional users of timber market models include government agencies, timber companies, private landowners, and non governmental organizations. As policy questions turn from pure market analysis to interdisciplinary research efforts, timber market models are being used to address a wider variety of questions.

Not only do models differ in theory and structure, ranging from spatial equilibrium regional models (Adams and Haynes, 1980) to dynamic optimization global models (Sedjo and Lyon, 1990), but their outputs differ as well. Given these differences, this paper compares model theory and structure to provide insight to model users and, potentially, new model developers. Understanding differences can help model users determine which are most appropriate for particular policy question, and it can help users interpret results, particularly when models come to different conclusions about similar phenomena.

The paper begins with a comparison of the economic theory and structure of four existing timber market models. It then compares past market predictions to actual market behavior. This paper does not attempt to find the best timber market model. Instead, it characterizes major model distinctions to determine how differences may impact market predictions. It also suggests how the results can be interpreted by readers and users.

The four models are the Timber Assessment Market Model (TAMM; Adams and Haynes, 1980), the CINTRAFOR Global Trade Model (CGTM; Cardellichio et al., 1989), the Timber Supply Model (TSM; Sedjo and Lyon, 1990), and the North American Pulp and Paper Model (NAPAP; Ince et al., 1994a). All models except for the NAPAP model have been in the literature since the mid or early 1980's, with the TAMM model having the longest historical record of activity. The NAPAP model in its current form is a relative newcomer to timber market modeling, although it is a substantially revised version of and earlier model (see Gilles and Buongiorno, 1987). Including NAPAP is important and interesting because it captures a segment that generally has been ignored by other groups.

Although this paper considers only these four timber models, other regional and global models exist. These include industrial models, such as those developed by Resource Information Systems, Inc. (RISI), the

Forest and Agricultural Sector Optimization Model (FASOM; Adams et al., 1996), and the models of Lönnstedt (1986), and Lönner (1991). Since these other models contain many of the same characteristics as those discussed in this paper, the discussion here can be applied more broadly.

FOUR TIMBER MARKET MODELS

Timber market outlooks have been a part of federal land policy and industrial forestry in the US since before the turn of this century. For much of this century, "gap" models have been used to predict future market activity. The theory of the "gap" model is not complicated. On the demand side, predictions of increasing population and income would spur continued increases in the demand for wood. On the supply side, land was converted from forest to farm, and the regrowth of harvested stands would take years, if not decades, to re-stock the forest naturally. Insatiable demand for forest products was predicted to outpace the ability of forests to regenerate naturally, causing large gaps between the demand for and supply of timber. This logic in part spurred the creation of federal forest reserves, and it guided federal forest policy through much of this century.

What gap models fail to incorporate in a unified economic theory, however, is that the guiding hand of timber prices will equilibrate demand and supply. As scarcity increases, prices increase, and markets respond with more management and human planting, as began in the US south in the 1950's (Moulton et al., 1995). On the demand side, prices may ultimately be capped by recycling and substitutes.

In the 1970's, the Timber Assessment Market Model (TAMM; Adams and Haynes, 1980) provided the first theory of timber market activity that unified the demand and supply side. At the time, the TAMM model was unique not only because it employed economic theory in an empirical application, but it also made at least two other important contributions to the literature. First, TAMM recognized the spatial nature of both supply and demand in timber markets by making use of the theoretical structure pioneered by Samuelson (1952). Samuelson's model captures the transportation costs necessary to move products from manufacturing facilities to demand centers. Because the most productive forests are located remotely from the urban centers where most wood is demanded, transportation costs are an important component in the overall value of wood.

Second, TAMM captures both end-product and stumpage market behavior simultaneously by solving a model in which all market levels in all regions must be in equilibrium in each period. Demand for stumpage is related directly to demand for end-products, such as lumber, plywood, oriented strand-board, and paper, and the capital (capacity) available to manufacturers in each period. Demand for stumpage is derived from the production function for solidwood products. Timber supply is estimated separately, but the total timber supply in any period must equal the derived demand. TAMM's structure formally links the demand for products with supply, as timber stocks are projected through time with a growth-drain equation. Details of the mathematical specification of a multiple-market, static simulation model such as TAMM is shown in Appendix A.

While the TAMM model was developed in the late 1970's as a tool for the US Forest Service's Resource Planning Act (RPA) timber assessment, it has been modified significantly since. The authors have included softwood and hardwood markets, a Canadian model, other international trade relations, new capacity adjustment mechanisms, and a host of other changes. In recent years, TAMM has been used extensively for policy analysis of forestry sector issues within the US (Adams and Haynes 1990, 1991a, b; Winnett et al., 1993; and Sohngen and Haynes, 1997).

As with markets in general, timber markets have become increasingly global, with end products, and logs that are traded from country to country. Although the TAMM model does not account for trade among all regions of the globe, a similar theoretical and structural model was developed in the 1980's by the International Institute for Applied Systems Analysis to assess the global trade of forest products (Kallio et al., 1987). This model has been updated and now is called the Center for International Trade in Forest Products Global Trade Model (CGTM; Cardellichio et al., 1989).

The CGTM model operates similarly to TAMM in that it is a spatial equilibrium market model with multiple market levels. It differs significantly for two reasons. First, by including trading between at least 40 regions of the globe, it is global in nature. Trading can occur in both end product and log markets. Second, it models both solidwood and pulp and paper markets simultaneously, although it does not solve the pulp and paper sector endogenously. While not solving both markets endogenously is a limitation, CGTM is the first of the timber market models considered here to model these markets simultaneously.

A more recent addition to timber market models is the North American Pulp and Paper Model (NAPAP; Ince, 1994a, 1994b), which was developed by the US Forest Service to support the RPA Timber Assessment program. The main purpose of the NAPAP model was to develop an empirical model of pulp and paper markets for the US, as those markets had not been included explicitly in the TAMM model to date. The theoretical structure of NAPAP is similar to TAMM and CGTM in that it is a spatial equilibrium and static simulation model, but NAPAP carries considerably more detail. Because both solid- and pulpwood markets are related through price effects, use of residual outputs, and other factors, the US Forest Service has recently used TAMM and NAPAP together for purposes of market projection, as described by Ince (1994a and 1994b).

The Timber Supply Model (TSM: Sedjo and Lyon, 1990) completes the set of four models considered in this paper. It differs significantly from the previous three models in many regards. First, it rests on a different set of economic theory, stemming from the theory of renewable and non-renewable natural resources (Hotelling, 1931). It is often referred to as an optimal control model, which incorporates rational expectations. Rational expectations assumes that consumers and producers are perfectly rational and that they make decisions today that are, on average, consistent with actual future market activity. For example, if producers harvest timber today rather than tomorrow, the prices they receive today must provide them a better return on their timber investment than if they had waited until tomorrow.

Second, it considers only delivered log markets, and it aggregates both solidwood and pulpwood, as well as hardwood and softwood markets. Third, it is global, but the modelers do not monitor bilateral trade like CGTM. Finally, TSM allows the choice of timberland management (including regeneration and continuing management costs) investment to be determined endogenously by a rational expectations process. The mathematical fundamentals of the TSM model are presented in Appendix A for the interested reader.

COMPARING MODEL THEORY AND STRUCTURE

These models have both similarities and differences. In the discussion that follows, 10 differences between the models (Table 1) are analyzed. This comparison provides a set of objective criteria for understanding differences in model behavior. The first distinction is that each of these models can be classified into one of two broad **theoretical classes**: spatial equilibrium or dynamic optimization. Both concepts are rooted deep within the economics literature, and both provide a perfectly consistent theoretical basis from which to develop a model. In fact, the two theories could be merged to develop a spatial, dynamic optimization model, but forestry economists have not done this on the large scale yet (probably because of the computational problems associated with solving such a model).

Differences in **projection methods** allow us to compare how the models introduce the time dimension. Static simulation models (TAMM, CGTM, and NAPAP) solve for a market equilibrium in each period individually, beginning with the initial period and moving forward using the last period's solution to initialize important data, such as the state of the timber stock, for the next period. The TSM model uses an optimal control theory approach to solve all periods simultaneously. Such a concept may seem confusing, but this produces forward looking behavior, where decisions made today must be consistent with those made tomorrow. Solving every period simultaneously formally bridges the gap between the theory of rational expectations and the TSM. The implications of rational expectations in markets is that if landowners or timber mills are not making rational investment decisions today, they will be out of business tomorrow. Others who can make rational decisions will take their place.

Sohngen and Sedjo (1997) outline these differences, and present an empirical comparison for simplified, single region models. Their results suggest that static simulation and optimal control models will behave similarly under steady state conditions, but price, harvest and inventory behavior differ when markets are forced away from these steady state conditions. The differences are most notable when demand shifts outward, and when stocks are distributed unevenly among age classes. Smaller differences occur when inventory is affected by small annual perturbations over many years.

The difference between static simulation and optimal control models have direct implications for incorporating **harvest mechanisms** into models. The mathematical solutions to the TAMM, CGTM, and NAPAP models provide no theoretical mechanism for harvesting timber in different age classes. Presumably, timber of any age can be harvested, as long as no more timber is taken out of any age class than is physically available. Solving optimal control models, however, dictates that only the oldest timber is harvested in any particular period. This imposes Faustmann forester behavior on all timberland.

Clearly there are benefits and limitations of using the Faustmann formula for all land. The Faustmann formula is fairly well accepted for many ownerships, but it does not capture additional constraints that may be imposed on individual timberland owners, such as capital and cash constraints, or the desire to maintain timberland for purposes other than timber production (Gregory, 1955; Hagenstein and Dowdle, 1962; Hartman, 1976; Swallow et al., 1990; and Swallow and Wear, 1993). This problem can be addressed by incorporating multiple land classes with different sets of costs, but optimal control models become increasingly difficult to solve as more land classes are included. Thus, a balance must be struck between the number of alternative land classes used and ease of solving a model. For their part, static simulation models can easily introduce alternative behavioral assumptions that provide for harvests over multiple age classes, but these decisions are based on assumption rather than theory.

These results have different implications for policy analysis. Because timber is harvested strictly according to age class, it is clear in optimal control models how policies in one region will impact harvests across the entire model. Also, optimal control models are based on a theory that subjects industrial timberland to the strictest tests of economic sustainability. Behavior that does not measure up to the Faustmann formula will not remain competitive in the long run. In the static simulation models, however, it is not as clear what drives harvest or price adjustments when conditions change in one region or another. Capacity adjustments, for example, can slow down market adjustment considerably, and can even cause the opposite effect as would be predicted by an optimal control model.

The models incorporate different **regions**, and have a different global **scope**. TAMM and NAPAP are North American models. Within the US, however, these models include multiple supply and demand regions. CGTM and TSM, however, both are global, although they delineate regions differently. CGTM is by far the most comprehensive, as it attempts to model most major consuming and producing regions. TSM incorporates multiple regions, including emerging plantation regions, but models a large part of the globe as a “non-responsive” region. The non-responsive regions include the Former Soviet Union and China. Further, TAMM, NAPAP, and CGTM explicitly report **regional trading patterns**, while TSM does not.

As markets become more heavily influenced by worldwide events, global models are perhaps better suited for analysis. Data on markets in different regions, however, is often hard to find, so that developing and maintaining updated, accurate global models is a substantial task indeed. In general, one might expect that global market models would predict lower long term trends in timber prices, due to substitution possibilities. This result, however, will depend on a host of demand and supply factors, including elasticities, trade flows, market activity across regions, and the assumed area of accessible timberland.

TAMM, CGTM, and NAPAP include **multiple market levels**, where all market levels are solved simultaneously. TSM, on the other hand, solves only the delivered log market. The demand function for delivered logs in TSM is assumed to be derived from end-product markets for timber products, such as lumber, plywood, paper, or furniture.

Solving multiple market levels allows modelers to capture important interactions between the two market levels, as discussed by Haynes (1977). For example, if demand for paper increases more rapidly than demand for solidwood, these models can capture the differential effects of both of these on both capacity adjustments, and harvests of the underlying natural resource. From the supply side, adjustments in technology may affect the utilization rates of stumpage or pulpwood for making end products, thereby shifting the rate of increase in demand for particular logs or stumpage. Furthermore, models with multiple market levels provide price and production estimates separately for stumpage and end product markets.

Capturing multiple market levels comes with a cost, however, as it requires complicated models of production processes. Particularly in long run analysis, it is hard to judge what processes will dominate the forest sector 20 or 30 years from now. Models of future capacity are therefore only as good as the underlying scenarios developed by the modeler.

The three models that incorporate multiple market layers have adopted different mechanisms for **adjusting capital** over time. These mechanisms all are “myopic,” in that they allow for sticky adjustments from period to period. Capital will adjust slowly over time, reacting to current timber prices and some scenario of technological change. This type of modeling varies from much of the economics literature where capital is modeled with dynamic models. The standing assumption in optimal control models is almost the exact opposite of this: processing capital can adjust instantaneously in response to the available timber inventory in harvestable age classes. In a sense, regions can turn their capital on and off at will in order to maximize the value of the timberland, rather than the value of the production machinery.

The differences between the sticky and instantaneous capital adjustment mechanisms can have a large affect on model predictions. In models with sticky adjustment mechanisms, despite a limited timber inventory in merchantable age classes, harvests may remain high because firms will pay higher prices rather than allow their capital to sit idly by. Prices will be bid up, providing landowners with incentives to harvest timber. In optimal control models, harvests instead jump from region to region, depending on where returns to timberland value are maximized (rather than the combined returns to timberland and process capital value). Harvest flows are often more uneven from period to period in optimal control models for any given region, although total harvests will be smooth.

All of the models utilize an **age delimited inventory**, although they take advantage of it to a different degree. Optimal control models use the age class structure to determine which inventory is harvested in any particular year. The static simulation models use the timber inventory only to calculate to the total volume of timber available in any period. While this affects the supply function, the impact on prices and harvests is less direct than in the optimal control models.

Finally, only the TSM endogenously determines **timberland management**. Landowners use predictions of future prices to determine how much management they are willing to put into timber today. If prices are rising, naturally, management intensity increases; if prices are falling, however, management decreases. TAMM, CGTM, and NAPAP instead determine timberland management by assumption or external prediction, using past trends. Different scenarios will answer policy related questions, such as how much different levels of management intensity affect price growth.

While these comparisons provide some insight into differences between the models, actual market projections remain as much an art as a science. Part of the art of predicting market behavior relies on assumptions about future economic and population growth, tastes, and timberland management. Alternative demand projections affect model projections significantly. Users must pay particular attention to these projections before following the “advice” of one model or another.

Traditionally, these models have been used to consider policy questions, rather than to predict market behavior. The models thus are well suited to address questions like: given current demand growth and consumption patterns, how much timber will we need 20 years from now to limit prices below a certain level, or what are the likely shifts in harvest patterns from region to region if the government bans log exports?

These models concentrate on predicting long term behavior, as evidenced by their use of 50 year time horizons. The models focus on long term average changes in price and consumption patterns over the next 50 years rather than short term analysis. They thus are not well suited to predict the impacts of cyclical or random shocks (such as business cycle activity), unless it is expressly incorporated into scenario analysis. Commercial or industrial models (such as those maintained by Resource Information Systems, Inc.) are more adept at predicting changes that result from cyclical activity because they tend to consider shorter time steps (i.e. quarterly), and they update their predictions with new demand assumptions more frequently.

ANALYSIS OF HISTORICAL MODEL RESULTS

Figure 1 presents historical and predicted southern softwood prices for runs published by three models over the past 15-20 years.[1] Historical data (termed “Actual” in Figure 1) for US southern stumpage price for the period 1952 to 1989 was obtained from Adams et al. (1988) and Richard Haynes (personal communication). Data from 1990 to 1995 represents an average of stumpage prices obtained from the Louisiana Department of Agriculture (Various Years), and southern pine stumpage prices recorded for Alabama (Timber Mart-South, 1996).

Note that the models actually report different price concepts. The TAMM80, RPA80, RPA89, and RPA93 runs predict US Southern stumpage prices, while TSM85, IIASA87, and CGTM89 predict US Southern delivered log prices. When interpreting model results found in the literature, researchers and users should be certain to understand what they are considering, because trends in delivered log and stumpage prices may differ over time. For example, the stumpage and delivered log prices will differ over time if harvesting or transportation costs vary. If these costs are increasing over time, then delivered log

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[1] The model runs presented in Figure 1 correspond to specific models and sources in the literature. The TAMM model is used for TAMM80 (Adams and Haynes, 1980), RPA80 (US Forest Service, 1980), RPA89 (Haynes, 1990), and RPA93 (Haynes et al. 1995); The CGTM model is used for IIASA87 (Kallio et al., 1987) and CGTM89 (Cardellichio et al., 1989); and the TSM model was used for TSM85 (Sedjo and Lyon, 1990). The NAPAP runs, although not shown in Figure 1, were derived from Ince et al. (1994a and 1994b).

prices will increase faster than stumpage prices, and vice versa if they are decreasing over time. TSM85 actually assumes that harvesting and manufacturing costs are constant over time, so that stumpage price trends will mirror those of delivered logs in Figure 1.

None of the models predict short term cyclical or random fluctuations accurately. For example, in the early or middle 1980's, it would have been very difficult indeed to predict that timber harvests would decline so dramatically in the US Pacific Northwestern region in the early 1990's, particularly since taxes also increased on Canadian imports to the US. In general, modelers have been very careful in pointing out this limitation of any particular scenario considered.

Since 1952, the average rate of growth of US Southern stumpage prices has been approximately 2.0% per year. Price predictions in Figure 1 range from 0.17% annual growth in TSM85 to 2.80% in IIASA87. Generally, earlier predictions tended to be higher than more recent predictions, except for TSM. Recent outlooks predict lower price growth because they incorporate expanded timber supply from recently established plantations, substitution of recycled material for virgin fibers in paper making processes, and enhanced global trade in timber products.

Large scale models predict regional price levels, which should not be interpreted as the prices that may occur at a specific location within those regions. The models aggregate harvests across large areas, and local market conditions can differ markedly from regional markets. In particular, one might expect more volatility in local prices and harvests for many reasons, including fewer opportunities for substitution and local shocks.

Prices for US Pacific Northwestern softwood is shown in Figure 2. Figure's 1 and 2 show that price trends between regions can differ significantly. TAMM, CGTM, and NAPAP model sticky capacity adjustment, which reduces the rapidity of shifts in harvests from region to region when resource conditions or policies change. These modeling attributes allows prices in different regions to diverge. In TSM, however, prices are arbitraged from region to region, so that the law of one price holds, and long term price trends in different regions converge.

TAMM80, RPA80, and IIASA87 predicted the greatest long term price appreciation, while TSM85 predicted the least. TSM85's lower prediction resulted from four different factors: lower predicted long term demand growth, predicted steady increase in plantation establishment in the emerging region (as point was noted by Binkley and Vincent, 1988), predicted increases in management intensity, and terminal conditions which impose a 0 % growth rate in demand after 50 years. While the plantation establishment rates in the TSM85 model run would appear to be fairly high (200,000 ha per year), actual plantation establishment in the tropical emerging region alone exceeded these annual rates in the decade of the 90's. 646,000 hectares were planted annually in South Africa, Insular Southeast Asia, and tropical and non-tropical South America between 1980 and 1990 (FAO, 1995). RPA89 and RPA93 both predict relatively higher prices during the early part of the next century, with some price moderation as demand from the baby boomer era dampens out. In contrast to the earlier IIASA87 outlook, CGTM89 predicted fairly moderate price growth throughout the 1990's.

NAPAP was run interactively with TAMM to develop the RPA93 model run (Ince, 1994a and 1994b). NAPAP actually predicts lower future pulpwood prices due to the influence new technologies in pulp manufacturing processes and recycling. The model, for example, predicts that recovered paper utilization rate increases 0.9 % annually between 1990 and 2040. Lower US prices and increased recycling rates thus serve to reduce woodpulp imports over the long run. These predictions influence the TAMM model, and they relate to the reduced price trends for US stumpage predicted by that model in the RPA93 run relative to RPA89 and RPA80.

DISCUSSION AND CONCLUSION

This paper attempts to clarify differences between the models by comparing model theory, structure, and output. Several implications can be drawn from the analysis. First, these models predict long term trends in price and harvest behavior. They cannot be interpreted to predict short term market phenomena related to cyclical or random events. Furthermore, prices are relevant for large aggregated regions; they do not represent specific local markets. Local prices can vary substantially from these projections.

Model predictions are no better than their input assumptions. Model scenarios of population and income growth, changes in taste, changes in timberland management, and substitute products will influence model predictions. Model users should carefully consider the input assumptions, and their potential influence on model results. For example, in the most recent RPA runs, population and income growth assumptions are similar to earlier runs. Differences in price projections are related mainly to updated assumptions over timberland management and new link between TAMM and NAPAP. The TSM85 prediction of low price growth relates to three key assumptions: low future growth in demand, high plantation establishment (relative to the other models), and terminal demand growth of 0% annually after 2035.

The TSM model predicts larger shifts in harvest levels from region to region than do the other models. This results from harvesting strictly by age class. When one region is short on timber in merchantable age classes, the model quickly substitutes timber from other regions. Static simulation models limit harvest adjustments from region to region because they capture capacity adjustment. Price adjustments, on the other hand, are opposite from this. Rather than shifting harvests from region to region, static simulation models shift prices. Thus, optimal control models will generally predict smooth price trends, and static simulation models may have periods of rapid or slow growth. Part of this difference results from the generally lower stumpage or delivered log demand elasticities used in static simulation models. Sohngen and Sedjo (1997), however, found these results even when the same elasticities were utilized, indicating that this is a general difference between the model types.

While there are many reasons to model global timber markets, global models do not appear to have done a better job than their North American counterparts in predicting US prices. This may result from the fact that North America is both the largest consumer and producer of timber products in the world, but it also results from the fact that North American models have incorporated exogenous models of end product and log market behavior in other regions of the world. Given the potential importance of tropical plantations, potential trade liberalization, economic growth in other regions, and large stocks of inaccessible timber in tropical and boreal regions, global market models are better equipped to deal with some policy issues of global importance.

Multi-market level models provide additional information related to end product prices, but they require substantial effort to understand and model technological change. We have thus seen that the multi-market models have become increasingly complex over time, as they have attempted to capture a panoply of different products and substitution possibilities. This analysis provides no clear evidence that multi-market models produce more accurate results than do single market level models.

Given the incredible complexity associated with modeling the future of market behavior and given that none of the models has perfectly predicted price trends, one must ask: what use are these models? Perhaps the best use of these models is in asking “what if,” rather than “how will,” questions. When most model projections are published, for example, the modelers go to great lengths to explain their assumptions and to present alternative scenarios. While modelers usually provide a best guess, scenarios play an important part in understanding how the model operates. Scenario analysis such as this is also frequently used for policy purposes. Recent examples include acid rain (Haynes and Kaiser, 1991) or climate change analysis (Binkley, 1988; Joyce et al., 1995; Perez-Garcia et al., 1997; Sohngen and Mendelsohn, 1996). Other analysis for which these models can used to assess price and harvest behavior are environmental pressures to reduce timber harvesting, clear-cutting, foreign trade disputes, foreign timber supply, plantation establishment, timberland management practices, recycling behavior, substitution possibilities, technological change, and non-industrial private timberland harvest behavior.

In final analysis, the models provide important, relevant information for timber market modeling, but the results must be interpreted appropriately. They are best suited to considering long term adjustments and policy analysis rather than short term, cyclical market fluctuations. The models, however, should always be considered in light of their input assumptions. Alternative scenarios provide additional insight to the importance of particular assumptions.

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APPENDIX A

This appendix presents a general mathematical formulation for the TAMM model, which is representative of the two other spatial equilibrium - static simulation market models (CGTM and NAPAP), and the TSM model, which exemplifies a dynamic optimization - optimal control model.

Spatial Equilibrium - Static Simulation

The spatial market models attempt to maximize consumer's plus producer's surplus minus the costs of transporting products to other markets. In any period, then, a generalized objective function to be maximized can be written:

$$\sum_i \int_0^{Q_i^D} D(Q_1 \ldots Q_I)\,dq_i - \sum_j \int_0^{Q_j^S} S(Q_1 \ldots Q_J)\,dq_j - \sum_i \sum_j C_{i,j} Q_{i,j} \;, \tag{1}$$

subject to

$$Q_i^D \le \sum_j Q_{i,j} \tag{2}$$

$$Q_j^S \ge \sum_i Q_{i,j} \;. \tag{3}$$

$Q^D{}_i$ is the quantity demanded, $Q^S{}_j$ is the quantity supplied, *D(·)* is the demand function, *S(·)* is the supply function, *i* is the demand region, *j* is the supply region, and $C_{i,j}$ is the cost of transporting from region *i* to *j*. As suggested by Adams and Haynes (1987), this type of model does not need to have a social welfare interpretation, although it implicitly maximizes the yearly value of net market welfare, minus transportation costs.

The market in (1) is presented in terms of the end product market. The next market level down, the stumpage, log, or pulpwood market, describes harvests of timber from forests and delivery to mills. In the above model, it is assumed to be described by the supply function, $S(\cdot)$. This supply function actually represents a complex set of interactions, including capacity and labor relations, a derived demand function, and a stumpage or log supply function.

Just as the supply function shown in (1) is derived from mill profit functions, a derived demand function is found as well. An equilibrium in stumpage, log, or pulpwood markets occurs when the quantity demanded equals the quantity supplied. In TAMM, CGTM, and NAPAP, wood supply functions are represented by

$$Q^S(t) = g\left(P_s(t), Inv(t)\right), \qquad (4)$$

where $P_s(t)$ is the price of stumpage and $Inv(t)$ is the total timber inventory. $Inv(t)$ is determined in any period with the following growth-drain equation:

$$Inv(t) = Inv(t-1) - Harvest(t) + Growth(t). \qquad (5)$$

Stumpage supply will therefore shift in or out depending on the size of the total timber inventory. Inventories will shift depending on annual harvests, timber yield, regeneration effort, and land use change. TAMM incorporates exogenous projections of regeneration efforts and land use changes by using the ATLAS (Mills and Kincaid, 1992) inventory projection system. The ATLAS model keeps track of inventories over time for different ownerships and timber types.

Thus, an equilibrium in both of these markets must exist in any period for the spatial equilibrium market models. TAMM and NAPAP do allow for log trading between regions, but the regions are limited to North America. CGTM on the other hand, allows for log trading across the globe.

Dynamic Optimization - Optimal Control

The formulation for the TSM model describes how dynamic optimization - optimal control models are generally formulated. The objective of TSM is to determine the path of timber prices and harvests that maximizes the net present value of net surplus (consumer's and producer's):

$$Max\sum_{0}^{T}\rho^{t}\left\{\int_{0}^{Q_t}D_t(n)dn-C_t\right\}, \qquad (6)$$

where $D_t\ (Q_t)$ is the demand function for industrial wood volume Q_t harvested in period t, and C_t is the total cost involved with harvesting and transporting timber to markets, and regenerating timberland in each period. Two laws of motion guide the movement of timberland acres from one age class to the next over time:

$$x_{h,t+1}=\left(A+BU_{h,t}\right)x_{h,t}+v_{h,t}e, \qquad \forall\ h,t \qquad (7)$$

$$z_{h,t+1}=Az_{h,t}+w_{h,t}e, \qquad \forall\ h,t \qquad (8)$$

where $x_{h,t}$ is the vector of timberland acres in type h at time t, $U_{h,t}$ is a vector denoting the proportion of acres that get harvested in each class and type h at t, $v_{h,t}$ is the area of timberland that is exogenously determined to be replanted at time t, and $z_{h,t}$ is a vector of management intensity levels for land already regenerated, and $w_{h,t}$ is a vector of management intensity for land regenerated in this time period. A, B, and e are matrices (or vectors) that describe the motion of acres from one age class to the next over time. Land that is harvested in any period is automatically regenerated with vector A, so that $v_{h,t}$ represents an additional set of acres that are exogenously assumed to enter forestry, such as plantations.

Consumers in this case are assumed to be timber mills and the demand function in (6) is a derived demand function, although no higher market levels are considered. Rather than solving period-by-period, a dynamic optimization model solves all periods simultaneously. This allows for rational expectations to occur, in that prices, harvests, and management intensity that occur in any particular period depend on today's and all future prices. The projections that consumers and producers use internally must be consistent with the predicted projections.

TABLES

Table 1: General characteristics of four timber market models.

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	TAMM	NAPAP	CGTM	TSM
THEORY	Spatial equilibrium (Samuelson)	Spatial equilibrium (Samuelson)	Spatial equilibrium (Samuelson)	Dynamic optimization (Hotelling)
PROJECTION METHOD	Static simulation	Static simulation	Static simulation	Optimal Control
HARVEST MECHANISM	N/A	N/A	N/A	Oldest Timber
SCOPE	US-Canada	US-Canada- +	Global	Global
REGIONS	~8	~8	~ 40	22
TRACKS REGIONAL TRADE	Yes	Yes	Yes	No
MARKET STRUCTURE	Multi-level	Multi-level	Multi-level	Delivered Log
CAPITAL ADJUSTMENT	Adaptive	q-theory	Adaptive	Rational
TIMBER INVENTORY	Age-delimited	Age-delimited	Age-delimited	Age-delimited
ENDOGENOUS MANAGEMENT	No	No	No	Yes

FIGURES

Figure 1: Timber price outlook comparison for US Southern softwood stumpage or delivered logs.

Figure 2: Timber price outlook comparison for US Pacific Northwestern West-side softwood stumpage or delivered logs.

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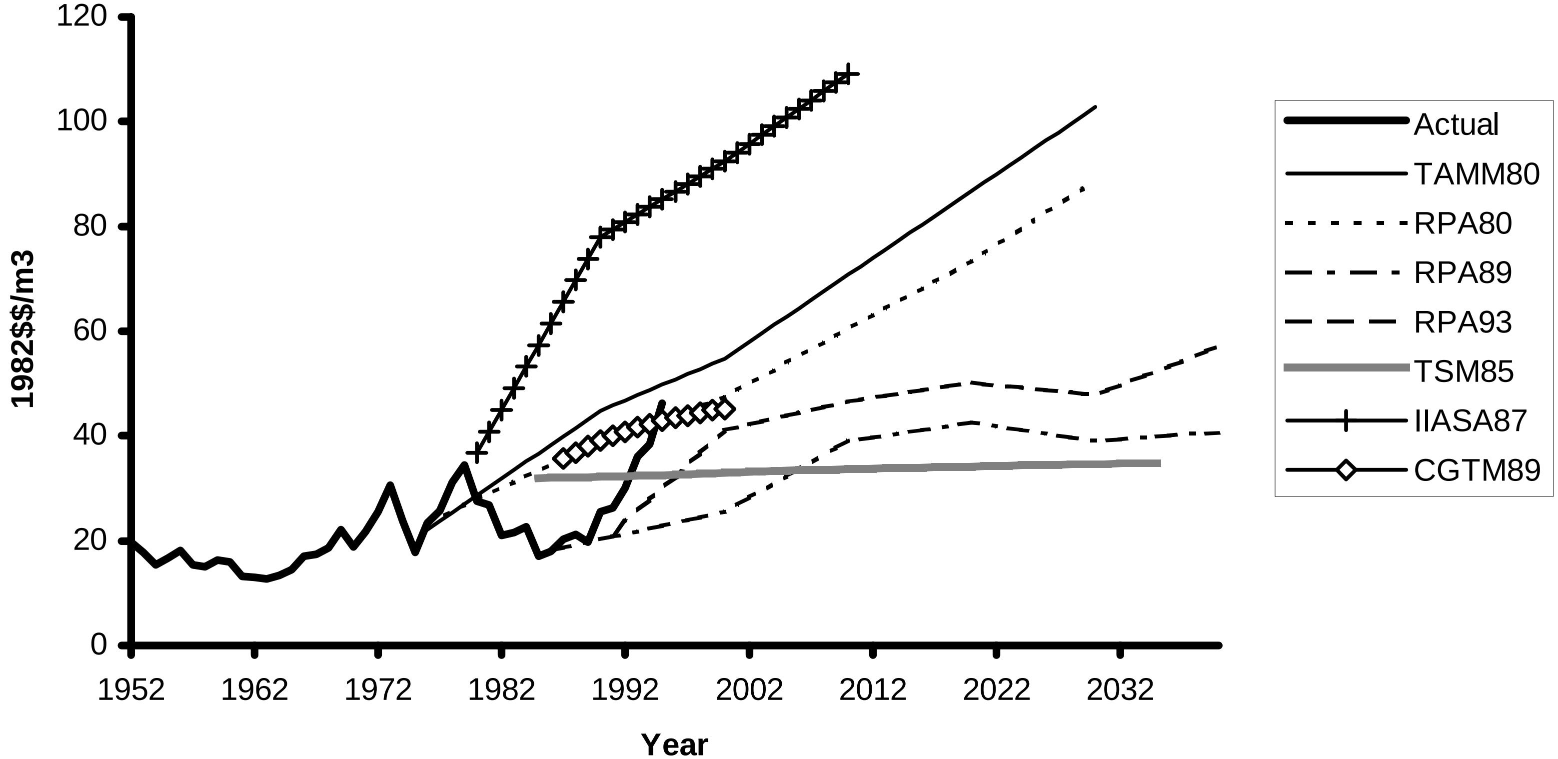

Figure 2: Timber price outlook comparison for US Pacific Northwestern West-side softwood stumpage or delivered logs.