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A DECISIONMAKING FRAMEWORK FOR ASSESSING ATMOSPHERIC DEPOSITION IMPACTS ON REGIONAL FOREST INVENTORY

by

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(ABSTRACT)

A decisionmaking framework was developed to assess atmospheric deposition impacts on regional softwood inventory in Virginia. This decisionmaking framework consists of three segments: a forest inventory projection model, a timber production function, and a timber consumption model. The Timber Resource Inventory Model (TRIM) was used to project future forest inventory, given initial inventory data, yield information, and harvest request. The timber production function allows the estimation of the individual effects of input variables on stand growth and yield. The timber consumption model was linked with TRIM to simulate the interactions between timber removals and inventory levels.

Algorithm analysis, sensitivity analysis, and an *a priori* analysis were used to examine the feasibility of TRIM for projecting atmospheric deposition impacts on inventory. Modification of growth and harvest decision variables in TRIM allows this impact estimation.

Schumacher's yield model was modified to develop the timber production function according to goodness-of-fit, minimal collinearity, and biological rationale. Crown length was used as a surrogate of a biological factor to reflect atmospheric deposition impacts on stand growth and yield. The small variance inflation factor allows the crown length elasticity to serve as a measure of the quantitative effects on the yield table. A system of predictor equations was added to the yield equation for simulating stand dynamics.

A consumption function approach was used to develop the timber removals model. The Box-Cox transformation, the stepwise regression procedure, and standard error were used to select the functional form, predictor variables, and estimates for the timber removals model. This removals model was linked with TRIM for simulating the interactions between removals and inventory levels for Forest Industry and Other Private. The existing forecasts of removals based on Forest Service projections were used for impact estimation for all ownerships.

This decisionmaking framework was applied to the softwood inventory data in Virginia to demonstrate the impact estimation. Sensitivity analysis showed that the percentage reduction of inventory and removals is directly related to the crown length reduction. The larger the crown length reduction, the greater the percentage reduction of the inventory. The percentage reduction of yield tables due to the crown length reduction is slightly less than the overall percentage reduction of the inventory but is slightly greater than the overall percentage reduction of removals. The quantitative information on atmospheric deposition impacts on crown variables is a key to the impact estimation for inventory and removals. Also, this decisionmaking framework can be used to measure some silvicultural practice effects on regional inventory.

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Chapter 1

INTRODUCTION

JUSTIFICATION

Harmful effects of acid precipitation, oxidants, and trace metals on forest growth in the Eastern United States have been hypothesized for decades. During the past years, large areas of the Eastern forest have been exposed to increased deposition of atmospheric pollutants. Increased pollution has resulted from the combination of increased industrialization and urbanization, a high density of fossil-fuel combustion plants, and auto exhausts. Reports of decreased growth and increased mortality of forest trees in these areas spurred atmospheric deposition research.

One of the potential problems caused by atmospheric pollutants is that the declines in forest growth might reduce the physical inventory and timber supply. The forest inventory is not only important to the forest industry which harvests the timber but it is also important to the large population which uses the forest's other multiple-use products. These products at least include recreation, hunting, water, and wildlife.

Although the exact impacts of atmospheric pollutants on forest growth are not yet determined and scientists are attempting to identify and quantify them, a decisionmaking framework should be developed concurrently. Once the biological information is available, the decisionmaking framework can be used to assess the potential impacts on forest inventory and timber supply.

A decisionmaking framework requires at least one forest inventory projection technique which can simulate the likely forest state for different possible levels of atmospheric pollutants. Inventory projection techniques have evolved from formulas through more elaborate diameter class models to highly disaggregated age class-ownership models. A newly developed forest inventory projection system, the Timber Resource Inventory Model (TRIM) (Tedder et al. 1987), simulates forest inventory changes over time in response to different levels of management and removals on forested areas.

It appears likely that TRIM will be used to assess regional atmospheric deposition impacts. There are several reasons. First, TRIM can be integrated with some econometric models, e.g. the Timber Assessment Market Model (TAMM) (Adams and Haynes 1980), which might be used to estimate timber supply impacts. Second, TRIM is designed to use USDA Forest Service Forest Inventory and Analysis data. These are the only regional forest inventory data available. It seems highly likely that any inventory models projecting regional biological impacts would use these data. Third, TRIM is already developed and documented. Thus, implementation time is likely to be saved by using a developed system rather than devising a new system.

The TRIM algorithm accepts exogenous yield tables and timber removal data. It contains neither biological models for simulating stand growth and yield nor timber market models for generating timber removal information. Since atmospheric deposition impacts on forest inventory are primarily through the biological growth of trees, quantitative analysis of stand dynamics is vital to the impact estimation. Recent studies on stand characteristics showed that stand dynamics can be projected by including some biological variables, e.g. crown size variables. The inclusion of some biological factors could provide the ability of stand growth and yield models to predict atmospheric deposition impacts on stand dynamics.

A timber production function approach to modeling stand growth and yield has proved useful for examining individual effects of environmental factors on timber production. This approach provides a possibility for examining input-output and input-input relationships by deriving various elasticities. If a timber production model includes some biological variables that are not affected by collinearity, the corresponding input-output relationship will provide the impact information. So, a timber production function approach is a useful tool for the impact estimation. It can also provide the yield tables needed for TRIM projections.

Timber removal information is a necessary input for TRIM to simulate forest inventory changes. Theoretically, timber removals are primarily determined by the timber market mechanism. Econometric market models should be the best approach to providing this information. Results from previous studies and collections of past market information give much knowledge of timber removal behavior. A pragmatic consumption function approach was used in this analysis.

Once a timber production function, a timber removal model, and TRIM are integrated together, one can use this decisionmaking framework to assess potential atmospheric deposition impacts on forest inventory. This framework will be useful for decision makers because the result will shed light on the possible adverse impacts of atmospheric pollutants on natural resources.

OBJECTIVES

The overall objective was to develop and demonstrate a decisionmaking framework for simulating the potential impacts of atmospheric pollutants on regional forest inventory. This overall objective was accomplished by four specific objectives:

1. Analyze the feasibility of TRIM to project atmospheric deposition impacts on forest inventory.
2. Develop a timber production model incorporating variables that can reflect atmospheric pollutant impacts.
3. Develop a timber removals forecasting model for projecting future timber removals.
4. Incorporate the timber production model and the timber removal forecasting model into TRIM to form a decisionmaking framework for simulating forest inventory changes over time in Virginia.

SCOPE

The decisionmaking framework developed in this study is limited to forest inventory changes over the next fifty years in Virginia. The initial inventory data used for this study are from the fifth forest survey. The total area of timberland in Virginia is 15,436,000 acres, 60.7% of the total area. The timberland produced 595,600,000 ft^3 of roundwood timber products in 1984, including sawlogs, veneer logs, pulpwood, fuelwood and other industrial products (USDA Forest Service 1987a).

The development of a timber production model is limited to loblolly pine (Pinus taeda) because it is the most important commercial timber species in this region and is the species for which the most data are available. One hundred seventy one sample plots selected from the Piedmont and Coastal Plain region were used for this study. These data represent stand growth and yield in loblolly pine plantations. Once a timber production function is fitted to these data, the corresponding input-output relationship was used to approximate similar relationships for other softwood species. Hardwood species were excluded from this study.

The study of timber removals is limited to Virginia. Timber removals include roundwood products, logging residues, noncommercial thinning, and timber inventory losses due to the diversion of timberland to other uses. Once the forecasting model is developed, the projection of timber removals will not be affected directly by atmospheric pollutants. That is, atmospheric pollutants' impacts are only through the biological yield tables.

The base-line yield tables used as input for TRIM were developed by McClure and Knight (1984). These yield tables were developed empirically from the average conditions observed on Forest Survey plots and are the best representative of stand growth and yield conditions by species, management intensity and site quality. The input-output information from the timber production model was used to modify these yield tables.

PROCEDURES

This study was divided into the four objectives and integrated as these objectives were accomplished. Each objective was treated as one self-contained topic so the following chapters associated with each objective was in a publishable paper format. Detail of procedures for each objective appears in each chapter.

The first objective was to examine TRIM's feasibility for projecting forest inventory changes in response to different levels of atmospheric pollutants. The first step was to analyze the algorithms in TRIM that simulate the forest inventory changes over time. This analysis sheds light on the limitations and advantages of TRIM for purposes of the impact estimation. The second step was to identify candidate variables in TRIM that can be modified in order to project atmospheric pollutant impacts. This identification was based on knowledge gained from the TRIM structure, the timber production model developed in the second objective of this study, and the timber removal information generated in the third objective. The third step was to suggest procedures for modifying TRIM to project atmospheric deposition impacts. This step suggested methods by which the individual variables within the TRIM system specified in step two might be modified to allow projection.

The second objective was developing the timber production model. The first step was to develop a timber production function incorporating biological factors, which can reflect atmospheric pollution impacts based upon existing knowledge of forest biology and atmospheric pollution damages. This model was used to identify individual effects of predictor variables on stand growth and yield. The second step was the development of a system of predictor equations to project stand dynamics. There was one prediction equation for each predictor variable in the timber production function. Past work in forest biometrics provides guidance for adopting or modifying existing models for best fitting the data. The final step was to diagnose collinearity variables and extract input-output and input-input relationships, using various elasticities, from the timber production function. These results give guidelines for modifying the yield tables in TRIM and may also provide management guidelines for unpolluted stands.

The third objective was to develop a timber removals model. The first step was to review previous work and identify key variables that affect timber removal behavior. Past studies on the timber market mechanism and timber harvest behavior are available. This information provides the basis for developing a forecasting model. The second step was to develop a timber removals model using the data available. A thorough econometric analysis was not intended. Rather, a pragmatic approach for forecasting removals within generally accepted bounds and as a function of market variables is desired. A consumption function was a candidate model. The specification of functional form depended on the data available and statistical analysis.

The final objective was to integrate the timber production model and the timber removals forecasting model with TRIM to form a decisionmaking framework. This decisionmaking framework was applied to the inventory data in Virginia for simulating inventory changes over time. Sensitivity analysis was used to calculate the impact estimation with some hypothetical atmospheric pollutant levels. Particular care was taken to identify, suggest and test the linkages between TRIM and the timber production model and the timber removals model. Finally, the deficiencies in this decisionmaking framework for projecting atmospheric deposition impacts were examined.

Chapter 2

LITERATURE REVIEW

INTRODUCTION

The study on the forest inventory changes due to atmospheric deposition integrates several topics. First, strong evidence of atmospheric deposition impacts on tree growth is essential to support this study. Second, techniques to model these impacts on stand growth are needed to quantify this impact information. Third, inventory projection models are necessary to project these impacts on regional inventory. Finally, forecasting of future timber removals is needed to update the inventory changes.

A comprehensive literature review is useful to draw together the previous studies on each topic in this study. This review tried to provide and highlight the contributions of various researchers. The contributions addressed here provided a solid foundation for this study.

There are four topics in this literature review according to the nature of the problems. The topics are:

1. atmospheric deposition impacts on tree growth,
2. forest inventory projection systems,
3. systems for timber production models, and
4. timber removals forecasting models.

ATMOSPHERIC DEPOSITION IMPACTS ON TREE GROWTH

EVIDENCE OF TREE GROWTH DECLINES

Early and recent investigations have reported widespread, substantial, sustained decreases in the growth of certain tree species in the Eastern United States. Beginning in about 1955, both the USDA Forest Service and the Tennessee Valley Authority began investigating the decline of eastern white pines (Berry and Hepting 1964). Results showed that 10% of the dominant and co-dominant trees in 25 permanent plots died between 1956 and 1965.

Whittaker et al. (1974) used total harvest and stem analysis to measure temporal changes in total forest yields on sample plots on the Hubbard Brook in New Hampshire. They found that reduction in forest yield between the 1956-1960 and 1961-1965 intervals was 18%.

Growth studies by Cogbill (1977) showed that no synchronized regional decreases in radial growth of beech, birch, and maple in the White Mountains of New Hampshire and red spruce in the Smoky Mountains of Tennessee had occurred. However, McLaughlin (1985) reexamined the data and pointed out that the ring chronologies showed evidence of a declining trend from about 1960 until 1970.

Johnson et al. (1981) studied the growth rate decline in pitch and shortleaf pine the Pinelands region of southern New Jersey. Results indicated that about one-third of the pines exhibited a readily apparent, abnormal decline in increment size.

Johnson and Siccama (1983) conducted quantitative surveys to assess mortality and dieback in 32 stands of spruce in the northern and southern Appalachians. Results showed that 40% of the trees incurred a rapid shift to very narrow rings in the early 1960s, 20% showed suppression, and 40% were not affected. Subsequent examination of additional southern stands of red spruce and fraser fir in Virginia, Tennessee, and North Carolina showed similar patterns of reduction in annual growth rings of high-elevation species beginning around 1960 (Adams et al. 1985, Bruck and Robarge 1984, McLaughlin 1983).

Siccama et al. (1982) reported red spruce declined by half in basal area and density in virgin mid to high-elevation stands in the Green Mountains of Vermont between 1964 and 1979. Diminished growth rates and general low tree vigor indicated that the decline was continuing. A recent study by Hornbeck and Smith (1985) using 3001 dominant or co-dominant red spruce across New England and the Adirondacks showed that the annual growth in basal area increased consistently from 1910-1920 to 1960, but then fluctuated around a generally declining trend, and was reduced from 53% to 40% by the early 1980's.

Since the early 1970s, investigations have been continuing to elucidate the influences of photochemical oxidants on tree species indigenous to the mountainous terrain of Virginia and the Ohio River Valley. McClenahen (1978) measured vegetation in seven stands on the upper Ohio River Valley and found that species richness and evenness were depressed within the overstory. Benoit et al. (1982) studied 10 plots of white pines in the Blue Ridge Mountains of Virginia. Results showed that mean annual radial increment growth of the ozone sensitive trees was smaller than that of tolerant trees for the period 1955-1978.

Skelly et al. (1983) inspected several native species at 24 sites in Shenandoah National Park to define the geographic extent of visible leaf injury induced by ozone. They found visible injury to leaves and needles in white pine, yellow poplar, green ash, hickory, black locust, and hemlock. There was some indication that growth losses were occurring in trees with and without visible injury.

Recently, the results from the Forest Responses to Anthropogenic Stress (FORAST) study showed that the growth trends of red spruce from each of four locations in the Northeast exhibited a similar pattern of recent decline as reported by Johnson and Siccama (1983). Similar symptoms of reduced crown vigor and reduced growth were occurring in red spruce in the Smoky Mountains of Tennessee and in the pine collection from Signal Knob in northern Virginia (Phipps 1983).

One of the most relevant findings for this study was from the report by Sheffield et al. (1985). They found that natural pine forests in the southeastern U.S. were growing more slowly than they were two to three decades ago. In the Piedmont region, naturally regenerated forests owned by small nonindustrial owners experienced the most slowdown in radial growth. In the Coastal Plain regions, the growth reduction occurred two decades ago followed by a decade of stable but slower growth. Growth rates of natural forests in the Piedmont Plateau decreased over both of the last two decades.

POSSIBLE CAUSES OF TREE GROWTH DECLINES

There are several possible causes of tree growth declines reported from the previous studies. Some studies used statistical methods to correlate tree growth to several possible variables. The others used controlled exposure experiments in laboratories to examine the suspected causes.

Phillips et al. (1977a, 1977b) applied regression analysis to examine the relationship between stand growth fluctuation and the arsenal production levels in Radford, Virginia. Results showed a significant inverse relationship between annual radial increment growth in two loblolly stands and arsenal production levels. This implied that the level of local air pollutants might affect stand growth and yield to some extent.

Johnson et al. (1981) used multiple regression and multivariate analysis to examine the radial growth rate decline in pitch and shortleaf pine. Results indicated that stream pH, drought, winter temperature, winter moisture, spring and summer insolution were significant variables related to growth, whereas ozone and sulfate dioxide did not appear to be involved in the shift of diminished growth. Since those variables might correlate with each other, these results were not conclusive.

Puckett (1982) used tree-ring indices of white pine, eastern hemlock, pitch pine and chestnut oak to regress against values of temperature and precipitation in order to derive a response-function relationship. Results suggested that the relationship of tree growth to climate has been altered by other unknown factors.

McLaughlin (1985) reviewed the forest decline studies mostly conducted using statistical methods. McLaughlin concluded that the diversity of sites, species, and stand conditions and the consistency of the pattern of observed decline symptoms were strongly against silvicultural factors, disease, and regional drought as primary stresses in the observed declines. He pointed out that ozone, wet and dry deposited strong acids, heavy metals, and climatic change might have direct and indirect influences on tree growth. Although this review provided a critical point for the state of art knowledge about the effects of air pollution on forests, it raised more questions than it answered.

Sheffield et al. (1985) suspected several possible causes for the growth reductions in the southeastern region. These causes included: (1) atmospheric deposition, (2) aging of stands, (3) increased stand density, (4) increased hardwood competition, (5) drought, (6) lower water tables,

(7) loss of old-field sites, (8) diseases, and (9) combined effects. No single factor could account for this decline phenomenon.

Hornbeck and Smith (1985) suspected that the possible causes of red spruce growth declines might include defoliation by the spruce budworm, climate change, maturation of the forest, and acid deposition. Since the data used in that study were not collected from controlled experiments, some possible environmental factors might not be included in this cause-and-effect analysis.

Pye (1987) reviewed 24 controlled exposure studies of impacts of ozone on tree growth and yield. Pye concluded that although clear evidence of broad susceptibility to levels of ozone was present, extrapolation of seedling impacts to stand or regional level was not yet possible. Pye's point is related to a common problem, how laboratory research results are extrapolated to field conditions. Even if one can set up a controlled field experiment, it is still difficult to isolate pollutant effects from other factors.

HYPOTHESES OF ATMOSPHERIC POLLUTANT EFFECTS ON TREE GROWTH

Among those possible causes of tree growth declines, scientists are more concerned with the anthropogenic causes because these causes might be ameliorated through the restricted use of fossil-fuel. There are several hypotheses of atmospheric deposition effects on tree growth.

Tamm and Cowling (1976) hypothesized several of atmospheric deposition effects on tree growth, including direct foliar damage, increased predisposition to stress, effect on reproductive processes, and alteration of leaf- and root-exudation processes. Pye (1987) reviewed the effects of ozone on the growth and yield of trees and speculated that prolonged exposure to ambient ozone levels could significantly reduce biomass growth, height growth, and photosynthesis of trees.

McLaughlin (1985) reviewed the effects of air pollution on forests and made several hypotheses of air pollutant effects on tree growth. First, atmospheric pollutants might directly affect tree growth by their diffusion through the stomatal pores of foliage. Second, pollutant dissolution in water in the mesophyll cells of the walls of the substomatal cavity can alter a wide variety of biochemical and cytological processes. Ultimately, these diffusion and dissolution can affect plant growth and development. Also, atmospheric pollutants could indirectly affect tree growth by altering plant-water relations and nutrient status of trees.

SUMMARY

Stand growth and yield are determined by many factors, including genetic potential, the innate productive capacity of lands, the extent to which the innate productive capacity is utilized, cultural treatments applied, climate factors, and environmental factors. These factors always combine together to affect stand growth and yield. Even if clear evidence of forest decline was found, the time and effort needed to clarify the possible causes are enormous. Atmospheric deposition is one of the possible causes that concern scientists because it is directly related to the use of fossil-fuel. So, we can not exclude this possible pollutant as adversely affecting tree growth, but it has not been proven either.

FOREST INVENTORY PROJECTION SYSTEMS

Basic information about forest inventories such as forest area, timber volume, ownership, biomass, prospective supply and demand, and related information are essential in the formation of management decisions. Everyone engaged in evaluating forest resources, whether from the standpoint of long-term development planning, large regional surveys, or local management planning, requires this information.

Since forest resources are continuously changing, the process of updating forest inventory is important for effective timber management decisions. For example, the timber inventory models are the core of long-term timber supply projection models. They provide an accounting system for tallying changes in the inventory due to harvest and area changes.

INVENTORY PROJECTION MODELS

Many of the early inventory projection techniques were crude extrapolations of growth and cut. Due to the advent of better data and computers, the number and sophistication of techniques capable of projecting timber resources into future are increasing rapidly.

Leuschner (1971) proposed a conceptual model to project long-term timber supply and inventory. In this conceptual model, total volume of inventory in any time period was projected using exogenous estimates of (1) supply and demand to determine annual cut, (2) changes in a acreage, and (3) net growth.

Larson and Goforth (1974) developed the Timber Resource Analysis System (TRAS) to prepare comparable timber resource statistics, to reconcile the differences between net growth and removals with changes in inventory volume between surveys, and to calculate the annual changes in numbers of trees by 2-inch diameter classes. Annual change was obtained by subtracting annual removals and mortality from the annual increase in number of trees in the absence of cutting or mortality. The number of trees for any year of the projection period are multiplied by volume per tree to produce estimates of volume, growth, mortality, and cut per acre. For the past years, TRAS has been used by the Forest Service with TAMM to project the future timber supply.

Although TRAS is computationally efficient, it has some limited capabilities. For example, TRAS requires an estimate of ingrowth trees, but ingrowth is difficult to estimate since ingrowth trees are not only generated from planting but also through natural seeding after harvest. It is also difficult in TRAS to project the changes in stand density after growth and mortality. Also, the use of TRAS was cumbersome in simulating management intensity changes, because it was originally developed to operate under the assumption that radial growth, mortality, and ingrowth relations remain stable over time.

Beuter et al. (1976) developed the Oregon Timber Resource (OTR) model for projecting future timber resource conditions in Oregon, based on the assumption that land use changes, management intensity, and economic indicators follow past trends. Some of the advantages in OTR model were in its highly disaggregated age class-ownership approaches, using existing inventory data as its input and considering management intensity. However, this model was designed only to meet the projection of specific stands, geographic area and period.

Later, Tedder et al. (1980) developed the Timber Resource Economic Estimation System (TREES) in which the inventory projection model was derived from the OTR model. The inventory projection model retained the positive aspects of TRAS while overcoming the lack of biological realism and difficulties in simulating the effects of intensive management.

Tedder et al. (1987) developed the Timber Resource Inventory Model (TRIM) by enhancing the capability of the inventory projection model in TREES. TRIM is an area-based, yield-table system that projects volume and acres by detailed strata for periods consistent with inventory stand-age classes. In TRIM, the inventory is represented by an array of acreage units and the corresponding volume per acre classified by ownership, management type, site class, stocking level, management intensity, and age class. Acreage is shifted among the units, and volume and growth estimates are derived from acreage movements through assumed yield tables.

TRIM can easily simulate shifts in management intensity and consequent changes in yields based on alternative assumptions about the future. However, TRIM does not allow separate stand projections for mixed age stands. All volume in a stand is assumed to be removed at harvest, and harvest acres may enter any acreage cell or leave the timberland base entirely.

Recently, Abt (1986) developed the State Allocation Of Regional Inventory Model (SARI) to estimate state shares of regional growth, removals, and inventory changes according to acreage changes. The USDA Forest Service (1987a) used this model and TAMM to project forest inventory, timber removals, annual growth, and timber supply from each state in southeastern region.

TRIM

TRIM is composed of four computer programs: BRUSCN, GRUSCN, ACUSCN, and TRIM. BRUSCN processes the initial inventory data, examines the data for errors, and prepares the inventory for use in ACUSCN and TRIM. GRUSCN reads the control and management information, processes the input data, and prepares this information for use in ACUSCN and TRIM. ACUSCN reads organization and removal data, combines inventory data and control and management data, and summarizes this information for use in TRIM. TRIM reads this information for performing the requested projection.

TRIM input is organized at three levels: (1) initial inventory for BRUSCN; (2) yield and management for GRUSCN; and (3) organization and removals for ACUSCN. The output from TRIM consists six types of reports, including inventory report, harvest report, alternate volume measure report, regeneration/cultural treatment report, economic report, and land shift report.

The initial inventory data are read by BRUSCN and processed into a binary random access file, BRURAF, which is used when ACUSCN is run. Yield and management data are read by GRUSCN and processed into a binary random access file, GRURAF, which is used by ACUSCN.

Organization and removals data are read by ACUSCN and combined with BRURAF and GRURAF into a binary random access file, BIGRAF. The TRIM program uses the BIGRAF data to perform the requested inventory projection.

TRIM is the core of this system. It provides the necessary algorithm for projecting inventory changes. The forest inventory is projected based upon the initial stocking levels and the yield tables. Growth volume is computed by subtracting the inventory after harvest from current inventory levels. Total harvest volume equals exogenous harvest plus endogenous harvest. The exogenous harvest is the sum of volume obtained from conversion of acres from one species to another, commercial thinning, and mortality salvage. The endogenous harvest is determined by harvest request and available harvest. Once the harvest has been allocated and removed, regeneration occurs for the acres just cutover and the acres that have been shifted into the timberland base from the unstocked category.

SUMMARY

The selection of forest inventory projection models depends on several factors. These factors include: (1) capability to project inventory for broad ownerships and species; (2) compatibility with existing inventory data; (3) capability to simulate all stand structures; and (4) consideration of timber removals. The review shows that TRIM is designed to use USDA Forest Service Inventory and Analysis data. This is the only regional forest inventory data available. The output from TRIM provides detailed information for net growth volume, inventory, timberland area, and actual harvest volume. The algorithms in TRIM can simulate harvest, regeneration, and inventory computation. Also, TRIM can project inventory for small or large forested areas. Although there are some deficiencies in TRIM, this model is feasible for this study.

TIMBER PRODUCTION FUNCTION MODELS

Traditional stand model approaches are based on the concept that the stand growth and yield are largely determined by four factors: stand age, site quality, stand density, and cultural treatment applied (Clutter et al. 1983). The first stand models for loblolly pine were developed by MacKinney et al. (1937) and Schumacher (1939). Their stand models involved the logarithm of some measure of stand production as the dependent variable and the reciprocal of stand age and some measures of site quality and stand density as predictor variables. Numerous studies subsequently used similar functional forms for predicting current volumes for loblolly pine stands (e.g. Clutter 1963, Goebel and Warner 1969, Burkhart et al. 1972a, Burkhart et al. 1972b, Amateis et al. 1986). Although useful in predicting timber growth and yield, many stand models might not be able to examine the individual influence of predictor variables on stand growth and yield because of collinearity.

TIMBER PRODUCTION FUNCTION APPROACHES

Several studies have shown that estimating timber production functions permits the examination of individual influence of the input variables on timber output. In forestry, production function approaches have been used to examine the effect of discrete treatments such as fertilization, spacing, and irrigation on stand growth. Nautiyal and Couto (1982) showed that a timber production function could be used in forest management. Later, Rawat and Nautiyal (1985) applied a logarithmic timber production function for economic analysis in intensive forest management. Those results suggested that timber production function approaches could be used in intensive forest management for examination of the interrelation between predictor variables, prediction of timber output, control of silvicultural practices, and economic decision making.

Timber production function approaches also could be useful in assessing the environmental impacts on timber production. Duerr (1979) suggested that biological and environmental factors could be included in timber production function models. Nautiyal and Couto (1984) demonstrated this concept using a polynomial production function to estimate stand growth as a function of stand age, basal area, nutrient, water, and solar radiation available to the tree over the growth period. They indicated that a timber production function could incorporate some biological or environmental factors such that timber production was estimated by these factors.

Several studies combined traditional stand model approaches with production function approaches to estimate current stand yield. Nautiyal and Couto (1982) used a logarithm-reciprocal production function to estimate logarithmic stand yield as a function of reciprocal stand age and stand density. Chang (1984) used the same functional form to demonstrate stand yield as a function of stand age, site quality, and stand density. Later, Rawat and Nautiyal (1985) used a logarithmic model to estimate stand yield as a function of stocking, generation number, and age. This model was used to determine the optimal stocking and the number of coppice harvests that would maximize the expected annual land rent.

The distinction between the traditional stand model approach and the timber production function approach lies in the criteria used. The traditional stand model approach emphasizes goodness-of-fit. So, the resultant stand models were generally the best-of-fit for the growth data. The timber production function approach usually requires examination of biological rationale and collinearity, as well as goodness-of-fit. Also, the functional form selected should be consistent with the production process. The fitted production function can then be used to examine the input-input and input-output relationships. The selection of functional form and predictor variables becomes a tradeoff among these criteria.

COMPATIBLE SYSTEMS OF STAND MODELS

When remeasurement data became available, the analysis method for modeling stand dynamics could be based on two axioms (Clutter et al. 1983). First, the basic Schumacher yield equation would serve as the model for predicting current yields. Second, any equation developed for prediction of growth should be compatible with the Schumacher yield function. The compatibility between stand growth and yield requires that the algebraic form of the yield equation could be derived by mathematical integration of the growth equation. So, compatible growth and yield equations should be used to fit the data.

Clutter (1963) initiated this approach and Sullivan and Clutter (1972) extended this method. Later, Burkhart and Sprinz (1984) developed a loss function to estimate the parameters in Sullivan and Clutter system of equations. Results showed that the resultant estimators were more efficient and stable. Chang (1984) showed a different approach to obtaining compatible growth and yield functions using differentiation and integration methods. Chang's approach could provide some flexibility for fitting compatible growth and yield equations.

Serial correlation results when using remeasurement data. There are at least two sources of serial correlation. One results because permanent plot data might induce serially correlated measurements. The other results because certain coefficients in the volume equation are functionally related to coefficients appearing in predictor equations and residuals from these equations are correlated. The differentiation and integration method suggested by Chang (1984) could improve the first source of serial correlation. For the second one, Furnival and Wilson (1971) suggested that simultaneous equation techniques used in econometrics could be used to efficiently fit these systems of equations. Murphy and Sternitzke (1979) and Murphy and Beltz (1981) applied this method to fit systems of stand models for loblolly and shortleaf pine, respectively. Borders and Bailey (1986) pointed out that a system of equations should first be converted into the reduced form and then fitted by a three-stage least squares technique. Borders and Bailey showed the correct procedure to convert into the reduced form. Then they used restricted three-stage least squares to fit the reduced form of a compatible system of stand models. Those results showed that the measures of goodness-of-fit and precision were nearly as good with their approaches as with the conventional unrestricted least squares approaches.

Murphy (1983) used the seemingly unrelated nonlinear regression technique to model a timber yield equation system for loblolly pine. Results showed that the equation system approach could retain the advantage of a stand model while providing better estimates through the use of additional stand density information. Murphy strongly recommended these simultaneous equation techniques when stand models evolved into a set of interdependent equations.

SUMMARY

Traditional stand model studies indicated that stand growth and yield are largely determined by stand age, site quality, and stand density. Timber production function approaches also indicated that timber growth and yield could be expressed as a function of stand age, site quality, stand density, and some biological factors. When remeasurement data are available, a compatible system of equations can be used to describe the stand dynamics using simultaneous equation techniques. This information provides the foundation for a system of timber production models to assess the impacts of atmospheric deposition on forest inventory.

TIMBER REMOVALS MODELS

Stumpage output and price theoretically are determined by the interaction of timber demand and timber supply (Gregory 1987). The demand for stumpage is derived from the demand for wood products, since stumpage is required when lumber, pulp, plywood, or any wood product is to be manufactured. The factors that influence timber supply might include ownership, utility, reservation price, and inventory.

Most of the econometric models developed in forest economics have estimated demand and supply simultaneously in the lumber and pulp markets. Methodologically, supply and demand estimation for stumpage should be closely related to those models for lumber and pulp markets. Recently Daniels and Hyde (1986) and Newman (1987) demonstrated solutions to the problem of supply and demand estimation in the stumpage market. Both studies estimated the supply and demand for stumpage directly using simultaneous equations of supply and demand. A two-stage least squares technique was used to fit the system of equations. Their results showed that the stumpage market mechanism could be described by the system of equations.

Although this simultaneous equation approach is attractive for this study, several problems exist. Demand determinants are likely to be different for different species. Stumpage prices are different for different species and ownership. Harvest behavior might be different for different ownership. Disaggregated economic data are needed to accommodate these problems. Also, the regional projection of timber removals includes net exports and non-commercial clearings. Additional projection for net exports and non-commercial clearings is needed.

PUBLIC SECTOR

Virginia timberlands are managed by National Forest, miscellaneous Federal, state, county and municipal, forest industry, farmer, corporate, and individual owners. In 1985, the public timberlands owned by National Forest, miscellaneous Federal, state, and county and municipal occupied 13% of the regional timberlands. The forest industry owned 12% and the other 75% was small private owners.

Stumpage supplied from National Forest and Other Public lands is primarily determined by policies (Gregory 1987). The early study by Hamilton (1970) suggested that a good correlation did not exist between the variations in National Forest timber sale volumes and the stumpage price changes. Buongiorno et al. (1985) supported this finding after examining if the volume offered on National Forests influenced, or was influenced by, the price of timber and lumber. Buongiorno et al. concluded that timber volume offered did not appear to have been influenced by timber prices. But timber volume can influence price if volume change is large enough.

One early study on timber output from public timberland in western Oregon and western Washington indicated that two factors might influence timber output (USDA Forest Service 1963). These included total acreage and quality of land available for commercial timber production and management practices. Berck (1979), in his study on the economics of timber, assumed that stumpage supplied from public lands was governed by an administratively set allowable cut. Berck used the historical public cut and USDA Forest Service projections of future public cut to estimate public supply. Berck concluded that public managers cut their forest more slowly than optimal.

Adams and Haynes (1980), in the 1980 Softwood Timber Assessment Market Model, assumed that public supply is a function of allowable cut and stumpage price. Adams and Haynes developed the following procedure to approximate changes in harvest levels.

1. Identify the future levels of allowable cut,
2. Estimate timber supply as a function of price and inventory, and
3. Compute final harvest levels by adjusting the levels of allowable cut and prices.

The assumption of this timber supply model for the public sector contradicted Buongiorno et al.'s (1985) conclusions. However, it might be helpful in projection.

PRIVATE SECTOR

Duerr (1960) initiated the hypothesis that the stumpage supply from the private sector was related to the existing timber inventory and the harvest decision. Private owners, based on the expectations of profitability, made the harvest decision to maximize their utility. This hypothesis was then used and modified to estimate timber supply from Virginia (Straka 1981, Greber 1983, Lawrence 1985, Clements 1987).

Straka estimated long-term timber removals from the nonindustrial forest sector in Virginia by regressing timber removals on alternative rates of return and timber inventory. The alternative rate of return was assumed to be a function of size of forest holdings. Results showed that size of forest holdings was a major determinant of timber output from the nonindustrial forest sector and alternative rate of return exhibited a strong negative correlation with size of forest holdings. Straka concluded that alternative rate of return was a primary economic variable in the nonindustrial forest sector.

Greber, in his study on a joint product timber supply, assumed that a stand would be harvested when current liquidation value exceeds the maximum expected present value of liquidation in some future period. Greber pointed out that the inability to recognize the price expectations could be a barrier to attaining a true timber supply model.

Lawrence, in his study on a short-term harvesting model, regressed harvest volume on current stumpage price, expected stumpage price, growth rate, landowner's discount rate, acres harvested, occupation of owner, age of owner, stand age, and total revenue. Results showed that current and past stumpage prices strongly influenced the harvest decision, while personal characteristics, timber stand characteristics, and the interest rate had no substantial impacts on the decision to harvest.

Clements, in his study on a timber supply model for southwest Virginia, assumed that harvest volume was a function of expected stumpage price. Clements pointed out that modeling individual landowner harvest behavior was one of the most difficult components of timber supply analysis.

Several other timber supply models also investigated the theoretical foundations of harvest behavior in private landowners. Binkley (1979), in his study on timber supply from private nonindustrial forests, concluded that stumpage price was a major determinant of timber harvest and that size of forest holdings and income of owners affected the propensity to harvest timber.

Berck (1979) pointed out that timber supplied from the private sector was determined by physical productivity of the land, land's management, and the harvest decisions. Berck concluded that private owners cut their woods more quickly than optimal.

Adams and Haynes (1980) developed short-term and long-term regional timber supply models for the private sector. The short-term model rested on two simple assumptions: (1) private stumpage owners would vary their cut directly with stumpage price; and (2) private cut would be greater if a greater stock was available from which to draw and less if the stock was reduced. The long-term model adjusted the level of management intensity and growth, future inventory, and cut through the short-term models.

SUMMARY

Timber removals can be estimated using simultaneous equations of supply and demand. Since demand determinants, stumpage prices, and harvest behavior might be different for different species and/or ownerships, disaggregated economic data are needed to accommodate these problems. Also, the projection of predictor variables is as important as the model development when these simultaneous equations are used for regional projection. It becomes difficult and time consuming to apply this simultaneous estimation. Instead, a consumption function approach is suggested in this study. This pragmatic approach for forecasting timber removals as a function of market variables might be a substitute to the simultaneous equation approach for the purpose of projecting future timber removals.

Chapter 3

TRIM'S FEASIBILITY FOR PROJECTING ATMOSPHERIC DEPOSITION IMPACTS

INTRODUCTION

A decisionmaking framework for assessing the impacts of different possible levels of atmospheric deposition on forest inventory requires a forest inventory projection technique. Many early inventory projection techniques were crude extrapolations of stand growth and cut. Due to the advent of better data and computers, regional inventory projection techniques have evolved from simple formulas through more elaborate diameter class models to highly disaggregated age class-ownership models. This study examined one newly developed forest inventory projection system, the Timber Resource Inventory Model (TRIM) (Tedder et al. 1987), in detail and assessed its capability to model the physical impacts of atmospheric deposition on regional forest inventory.

There are at least three reasons for choosing to analyze TRIM. First, TRIM is designed to use USDA Forest Service Forest Inventory and Analysis data. These are the only regional forest inventory data available. It seems highly likely that any inventory models projecting regional biological impacts would use these data. Second, TRIM is already developed and documented. Thus, implementation time is likely to be saved by using a developed system rather than devising a new system. Third, TRIM can be integrated with some econometric models to estimate harvest and examine timber supply impacts. For example, either the Timber Assessment Market Model (TAMM) (Adams and Haynes 1980) or some consumption function can be incorporated with TRIM.

The TRIM algorithms do not contain any biological models for simulating stand growth and yield. Atmospheric deposition impacts on forest inventory are primarily through the biological growth of stands, so one must determine if the algorithms are feasible for simulating these impacts, and, if so, which input variables need to be modified.

OBJECTIVES

The objectives of this study were two-fold: (i) to investigate capability of TRIM to project atmospheric deposition impacts on forest inventory; and (ii) to suggest modification of TRIM for projecting atmospheric deposition impacts.

PROCEDURES

The first step was to become familiar with the TRIM structure, the input data, and the output report, and then install the model on the Virginia Tech mainframe computer system. The second step involved analyzing the algorithms that simulate the forest inventory changes over time. The principal algorithms are harvest, regeneration, and inventory and growth volume computation. The third step was to identify candidate variables in TRIM using sensitivity analysis and an *a priori* analysis, which can obviously reflect atmospheric deposition impacts. The fourth step was to suggest methods by which the individual variables specified in step three might be modified to allow projections.

TRIM SYSTEM STRUCTURE

TRIM is an area-based, yield-table projection system designed and developed to model forest inventory changes over time in response to different levels of management and removals from either large or small forested areas (Tedder et al. 1987). TRIM has four computers programs: BRUSCN, GRUSCN, ACUSCN, and TRIM. The first three programs, BRUSCN, GRUSCN, and ACUSCN are data processing programs which scan all input values, flag illegal or unusual values, provide default values automatically, prepare summarized information for TRIM, and print compact reports. The TRIM program is the core of this system. It uses the data file created in ACUSCN to simulate harvest, regeneration, shift of management intensity, and inventory over the projection horizon.

Input data are organized at three levels: (i) initial inventory for BRUSCN; (ii) yield and management for GRUSCN; and (iii) organization and removals for ACUSCN (Table 1). The initial inventory is specified in a Basic Resource Unit (BRU). Yield and management information is specified in a Grouped Resource Unit (GRU). Organization and removals are specified in an Allowable Cut Unit (ACU).

The TRIM program writes six types of reports: the inventory report, the harvest report, the alternative volume measure report for inventory and harvest, the regeneration/cultural treatment report, the economic report, and the land shift report.

TRIM SYSTEM ALGORITHMS

The principal algorithms that simulate harvest, regeneration, and inventory computation are in the TRIM program. The following are considered the most important.

Growth and Inventory

Growth is estimated by calculating the inventory in two time periods and subtracting the two. The inventory is projected based upon the stocking level midpoint (SLMID) of the initial inventory and the selection of one of two options: a yield table option or an approach-to-normality option.

Timberland management intensity 1 has three stocking levels, while management intensities 2 to 5 have only one stocking level. Each stocking level has one SLMID. The value for the stocking level midpoint (SLMID) of the initial inventory is calculated as follows. First, the total volume for each age class is estimated by multiplying the volume per acre of the initial inventory by the number of acres. The same acres are then multiplied by the yield table volume per acre. The yield table volume per acre is called the standard volume. Both actual and standard volume are then summed through all age classes within that stocking level. The stocking level midpoint is the quotient of the actual total volume divided by the standard total volume for that management intensity and stocking level. They are used for both the yield table method and the approach-to-normality method.

When the value for GROTYP in the GRU is set to zero, the yield table method is used. The SLMID's are constant in all time periods when the yield table method is used. The stand volume per acre, VOLPA, multiplies the SLMID and the number of acres in each age class to estimate total volume at the end of each time period.

When GROTYP is one, the approach-to-normality method is used for inventory projection. The normality is adjusted up or down for the next time period depending on the current stand volume, the yield table volume, and the age class. This method uses a linear approach-to-normality equation, which projects the next period normality as a function of the current normality. Current normality is the stocking level midpoint (SLMID) before growth based on the values for the previous age class. For any age class with zero standard volume, current normality is set to the initial SLMID for that management intensity and stocking level. For all other age classes, current normality is the ratio of the sum of current volume per acre plus thinning volume per acre times the SLMID divided by standard volume.

Projected normality is the stocking level midpoint after growth computed for each age class. The linear approach-to-normality equation used to compute projected normality is:

$$PNOR = COEFAP + INTAP \cdot CNOR$$

where $PNOR$ = projected normality
$COEFAP$ = intercept of the equation
$INTAP$ = slope of the equation
$CNOR$ = current normality

Based on Forest Service estimate, $COEFAP$ is set to 0.90 and $INTAP$ is set to 0.11. For any age class with no existing acres, projected normality is set to zero. For all other age classes, the projected normality is further modified according to the age class, since older stands are assumed to have less growth. The rule for modifying the projected normality is:

$$FPNOR = \begin{cases} PNOR & \text{if age class} \leq FULLAP \\ CNOR + \dfrac{PNOR - CNOR}{2} & \text{if } FULLAP \leq \text{age class} \leq HALFAP \\ CNOR & \text{if } HALFAP \leq \text{age} \end{cases}$$

where $FPNOR$ = the projected normality used to calculate growth
$FULLAP$ = the last age class to receive the full increase in growth
$HALFAP$ = the last age class to receive one half of the increase in growth

After the projected normality is estimated, volume per acre for each age class after growth is obtained as the product of the projected normality times the standard volume per acre if the projected normality is less than or equal to the maximum proportion of stocking allowed, APLIM. For the projected normality greater than APLIM, volume after growth is equal to the volume before growth, and volume per acre after growth is the ratio of volume after growth divided by acres.

Finally, TRIM computes the growth volume by subtracting the previous inventory after harvest from the current inventory level. Then, the growth and inventory within each period are reported.

Harvest, Mortality, and Regeneration

Total harvest volume equals exogenous harvest plus endogenous harvest. The exogenous harvest is the sum of volume obtained from conversion of acres from one species to another, commercial thinning, and mortality salvage. The commercial thinning volume is obtained from the thinning table by age class and management intensity. These tables are determined exogenously by the analyst. The actual thinning volume is estimated by the thinning volume per acre, THINPA, in the thinning table adjusted by SLMID.

Mortality salvage is determined by the mortality volume per acre, MORTPA, in the mortality tables, the proportion of the salvage volume, MORPRP, and the minimum amount of salvage volume, MORVOL. If the salvage proportion of mortality volume multiplied by the mortality volume per acre is less than the minimum salvageable volume per acre, mortality salvage will not occur. All these variables are determined exogenously by the analyst.

The endogenous harvest is determined by the harvest request, available harvest, and exogenous harvest. The harvest request, HRVACU, is determined exogenously by the analyst for each ACU by time period. The available harvest is calculated by summing all available harvest volume down to the minimum harvest age class, MINHAR. The endogenous harvest is equal to the harvest request minus the exogenous harvest as long as there is sufficient volume in the available harvest to satisfy the endogenous harvest. Otherwise, endogenous harvest is set to the available harvest. The calculated endogenous harvest is then allocated to each age class according to the harvest sequence.

These relationships can be summarized as follows:

$$Ht = Hex + Hen$$

$$Hex = Hc + CT + MS$$

$$Ha = \sum_{i=MINHAR}^{oldest} V_i$$

$$Hen = \begin{cases} Hr - Hex & \text{if } Hr - Hex \leq Ha \\ Ha & \text{otherwise} \end{cases}$$

where Ht = the total harvest
Hex = the exogenous harvest
Hen = the endogenous harvest
Hc = the harvest from converting
CT = the commercial thinning
MS = the mortality salvage
Ha = the available harvest
V_i = the volume in age class i
Hr = the harvest request, the variable $HRVACU$

The exogenous harvest volume is estimated according to the yield and management information. The available harvest is determined by the inventory and the minimum harvest age class. The harvest request is obtained exogenously from some market model or consumption function estimators. Then the total harvest is the sum of exogenous and endogenous harvest.

The harvest sequence is determined by the preferred harvest proportion for each age class, HVPROP. If an oldest first priority is desired, enter 1.0 for the oldest age class and the harvest volume is allocated to the age classes in a descending order. If a proportion is to be harvested from several age classes, enter the proportion for each age class. Proportions must sum to 1.0 and enter in age classes equal to or greater than MINHAR. If harvest volume is not exhausted, the program reverts to an oldest first harvest priority. If volume is exhausted, it is removed relative to the amount of volume available in each age class to the harvest proportion for that age class. Also, the allocation of harvest request assumes that the substitution between softwood and hardwood is independent. So the softwood harvest request is allocated to the softwood stands only.

Once the harvest has been allocated and removed, regeneration occurs for the acres just cutover, and these acres that have been shifted into the timberland base from the unstocked category. These acres are initially restocked in the same management intensity they came from but they may shift to other management intensity according to the predetermined shifting of the acres.

CANDIDATE VARIABLE IDENTIFICATION

The TRIM system is analyzed to identify candidate variables for modification to simulate atmospheric deposition impacts. At least four types of forest injury can occur due to atmospheric pollutants: growth loss, mortality, increased susceptibility to secondary stresses, and visible injury. So, the candidate variables should be related to inventory projection, mortality, and the management decisions associated with inventory projection and mortality.

VOLPA is the very first candidate variable, for atmospheric deposition may decrease growth and decreased growth can be reflected through the changes of the yield tables. VOLPA is used by both the yield table and approach-to-normality methods to simulate growth. If the yield table method is used, only VOLPA needs to be modified to reflect growth effect.

When the approach-to-normality method is used, five other variables need to be considered for modification. These include: INTAP, the intercept of the approach-to-normality equation; COEFAP, the slope of this equation; FULLAP, the maximum age class to receive the full increase in projected normality; HALFAP, the maximum age class to receive one half of the increase in projected normality; and THINPA, the thinning volume per acre.

The second group of candidate variables related to mortality includes MORTPA, the mortality volume per acre, MORPRP, the proportion of the salvage volume, and MORVOL, the minimum amount of volume that can be salvaged. These could be modified to reflect atmospheric deposition caused mortality if subsequent research indicated it was an impact.

The third group of candidate variables is related to the management decisions which could be affected by the changes of inventory projection and mortality. These can be subdivided into control decision and harvest decision variables. Control decision variables include: ROT, the rotation age; SLDIST, the stocking level distribution of acres regenerated in stocking levels 1, 2, and 3 in management intensity 1; ODSTOC, the stocking level for each donor category upon entry into the timberland base; AVDIAM, the average diameter for each management intensity; THINPA, the thinning volume per acre; and APLIM, the maximum proportion of stocking allocated. These variables seem unlikely to be significantly affected but have been included for completeness.

Harvest decision variables are: MINHAR, the minimum harvest age class for each management intensity; HARGRO, the adjustment factor for growth on harvest; and HRVACU, the harvest request by period. Direct effects on these variables are unlikely. However, atmospheric deposition could change the physical timber inventory which in turn could shift supply. A shift in supply would cause a change in the price and quantity consumed, by some unknown amount, in the next time period. Changes in MINHAR should reflect changes in merchantability standards if they are expected.

SENSITIVITY ANALYSIS

Sensitivity analysis is used to examine which candidate variables cause obvious changes in inventory levels. The candidate variables whose change has little or no effect on inventory are not worthwhile investigating further because atmospheric deposition impacts upon them will have little effect on projected inventory levels. An *a priori* analysis, rather than actual computer runs, is used for some variables.

DATA

Virginia's fifth forest survey data were used for the sensitivity analysis. The data were aggregated by ownership, species, and site class at the state level. Accordingly, survey unit identification was lost. The data were divided into six ownerships, five species, and three site categories (Table 2). Therefore, there were 90 BRUs.

For each BRU there is one GRU to provide yield and management information. So 90 GRUs are used to run GRUSCN. The standard yield tables by age class and management intensity were developed empirically from the average conditions observed on selected survey plots (McClure and Knight 1984). Also, the thinning and mortality tables were estimated empirically from the selected survey plots (Brown 1986). No economic information was provided in the GRU's data.

One ACU provides organization and removals information for one ownership. So, there are six ACUs. The time information indicated that the starting year was 1985, and that there were seventeen 5-year age classes ranging from 0-5 to 86-90. The length of each projection period and age class is 5 years. The harvest request information was obtained from USDA Forest Service.

RESULTS

The initial GRU's information provides the approach-to-normality equation with an intercept of 0.11 and a slope of 0.90. The last age class to receive the full increase in growth, FULLAP, is 6 and the last age class to receive one half of the increase in growth, HALFAP, is 10. The minimum harvest age class in most GRUs is 4. The HRVACU in each period is from forest industry only. So the sensitivity analysis was performed using forest industry inventory data.

First, baseline runs were made for the yield table method and the approach-to-normality method. Table 3 shows that the approach-to-normality method projects more future inventory. Next, the candidate variables were modified and runs were made for each modification as follows.

GROWTH VARIABLES

Only VOLPA needs to be modified when the yield table method is used. VOLPA was reduced to 90, 80, and 70 percent for each time period and a run was made after each reduction. Table 4 shows that the projected inventory was reduced to 90, 80, and 70 percent, respectively, of baseline projection as time elapses. This implies that any reduction in VOLPA will eventually result in the same percentage reduction in inventory using the yield table method. When the approach-to-normality method was used and only VOLPA was modified, Table 5 shows that the degree of reduction in projected inventory is less but eventually approaches the same percentage reduction in VOLPA.

When the approach-to-normality method is used, the variables VOLPA, INTAP, COEFAP, HALFAP, and THINPA may be modified. First, VOLPA, INTAP, and COEFAP were simultaneously reduced to 90, 80, and 70 percent of the baseline value in each period. Table 6 shows that the percentage reduction in projected inventory is far greater than the percentage reduction in VOLPA, INTAP, and COEFAP. The changes in VOLPA, INTAP, and COEFAP have an obvious effect on the projected inventory.

Next, an *a priori* analysis shows that the changes in THINPA, FULLAP, and HALFAP have small effect on the projected inventory. THINPA has little effect because the entries in the thinning tables are available only for management intensity greater than one and only appear in one age class. The initial values for FULLAP and HALFAP are 6 and 10 respectively. If the harvest volume is large enough to remove the stands with age class greater than FULLAP, the changes in FULLAP and HALFAP will not alter the projected inventory. Otherwise, this effect is still trivial since only a small percentage change in normality will occur for some age classes due to the changes in FULLAP and HALFAP.

Decreases in VOLPA, INTAP, and COEFAP caused rapidly decreasing inventory. The more the percentage decrease in VOLPA, INTAP, and COEFAP, the larger the percentage reduction in the projected inventory. This suggests that changes in VOLPA, INTAP, and COEFAP impose a multiplicative effect on inventory. The reason is that the approach-to-normality method projects the future normality as a function of the current normality, which is already changed by the alteration of VOLPA, INTAP, and COEFAP. Thus, the change effects are accumulate in later time periods. Therefore, there would appear to be little reason to use the approach-to-normality method given our current knowledge of atmospheric deposition impacts.

MORTALITY VARIABLES

The candidate variables for mortality were analyzed on an *a priori* basis. Increasing mortality salvage volume will have a positive but small impact on the projected inventory according to the algorithms in TRIM. The volume of salvage mortality is added to the exogenous harvest, which in turn reduces the endogenous harvest for any level of HRVACU. The decrease in endogenous harvest will increase the future inventory. Further, current biological research indicates that widespread mortality caused by atmospheric deposition is unlikely. MORTPA could be increased if subsequent research reveals mortality impacts. Inventory impacts would then depend on the size of MORTPA.

MANAGEMENT CONTROL VARIABLES

The candidate variables for management decisions were also examined on an *a priori* basis. Variables related to the control decision are unlikely to affect projected inventory. The variable ROT is used only to calculate soil expectation value which provides a criterion for the shift among management intensities. The soil expectation value also depends on price, cost, and harvest volume. It can be shown that changes in ROT have little impact on the projected inventory using the soil expectation formula in TRIM.

The variable SLDIST is estimated by summing all acres and dividing that value into the number of acres by stocking level. This is done according to the inventory in the past 30 to 50 years. Undoubtedly, the stocking level distribution after harvest regenerated will be changed due to changes in stand growth and mortality. However, we have little information about the redistribution of acres when regenerated. If all the atmospheric deposition effects on growth and mortality are included in VOLPA, or possibly in the approach-to-normality equation, then we can probably use the initial SLDIST for the projection period.

The variable ODSTOC also remains constant for the same reason. The variable AVDIAM is used for reports only, so we need not modify it. The variable THINPA, as shown before, has little effect on the projected inventory. The variable APLIM is used with the approach-to-normality method to control the initial stocking level of the timberland acres. APLIM controls SLMID outliers so the changes of APLIM have little effect on the projected inventory.

HARVEST VARIABLES

Projected inventory is very sensitive to the changes in HRVACU and MINHAR but insensitive to HARGRO. First, HRVACU is reduced to 50, 30, and 20 percent of the baseline data in each time period. Table 7 shows that reduced HRVACU has obvious impacts on the projected inventory. Since the harvest request provided by Forest Service is far greater than the available harvest volume, the inventory projection reduces dramatically. The relative impact due to the change in HRVACU is around 100 percent during the later periods. When harvest request exceeds the sum of exogenous harvest and available harvest, increases of harvest request do not further decrease the projected inventory.

Next, the value of MINHAR was increased one age class over the baseline data. MINHAR determines the available harvest volume which can be cut. Increasing MINHAR will decrease the available harvest volume and may increase projected inventory. Table 8 shows that the projected inventory will increase if the value of MINHAR increases. However, when harvest request is small, compared to the available harvest, the projected inventory becomes large and the increases of MINHAR have little effect. The reason is apparent. MINHAR determines available harvest and range of age classes for preferred harvest proportions. When harvest request is far smaller than the available harvest, the increase of MINHAR will not alter the actual harvest volume and so the projected inventory is unchanged.

The variable HARGRO is calculated from the yield tables and is used to adjust available harvest. HARGRO will remain unchanged if VOLPA in the yield tables are modified by equal proportion.

SUMMARY

Groups of candidate variables in growth, mortality, and management decision functions might be modified to reflect atmospheric decision impacts. Growth and harvest decision variable changes obviously affect the projected inventory. Only the variable VOLPA need be modified when the yield table method is selected.

Three variables, VOLPA, INTAP, and COEFAP, have a large effect on projected inventory when the approach-to-normality method is used. Changes in VOLPA, INTAP, and COEFAP cause multiplicative changes in stand growth. However, information on the dynamic changes in stand growth due to atmospheric deposition and its influence on INTAP and COEFAP is currently unknown. This information is needed to modify the variables using the approach-to-normality method.

HRVACU greatly affects inventory projections among the harvest decision variables. When the harvest request is greater than the sum of exogenous and available harvest, the changes of MINHAR have an obvious effect on the projected inventory. Otherwise, MINHAR has a little effect. Since HRVACU is estimated exogenously, we need the information about how HRVACU is determined.

DISCUSSION

TRIM is most sensitive to either growth or harvest decision variables. One or the other is thus most likely to be changed if TRIM is to be used to estimate atmospheric deposition impacts. The more sensitive variables are desired so that even small changes caused by atmospheric deposition will be reflected in the final inventory. Biologically, atmospheric deposition will affect growth, or possibly mortality, so these are the tables which must be modified if the TRIM system is to be used for impact analysis.

Yield tables can be obtained from the information on Forest Survey plots or from published models, such as McClure and Knight (1984). But, those yield tables contain no separable information about atmospheric deposition growth impacts. Thus, additional information about how forest growth is changed by atmospheric deposition over time is needed. The TRIM system does not contain any biological growth simulation model which could be modified to estimate these atmospheric deposition impacts. Therefore, the capability of the TRIM system to project atmospheric deposition impacts depends on the availability of exogenous information.

A timber production function approach might be useful for providing exogenous information about atmospheric deposition impacts. When one incorporated some timber production function with biological variables, the partial elasticities of timber output with respect to these biological variables can be used to examine the individual effects on stand growth. With this information, one can modify the yield tables in TRIM and assess atmospheric deposition impacts on inventory.

HRVACU, the harvest request, has been shown to greatly affect ending inventories. This variable is appropriately determined by econometric models of stumpage supply and demand. For example, TAMM might be a candidate for this estimation. Another candidate approach is to use some consumption function to estimate the timber removals as a function of inventory, timberland area, and stumpage price. The actual harvest in TRIM includes precommercial thinning, mortality, and conversion of stands, so it is the timber removals rather than stumpage quantity that update forest inventory in TRIM. A regional projection should include net exports from that region and non-commercial clearings. Thus, econometric models with a national scope are required. A consumption function approach might be a substitute to the timber market model. This consumption function will accept inventory and timberland area information from TRIM and stumpage price from some price expectation model to project timber removals for TRIM.

CONCLUSIONS AND RECOMMENDATIONS

Several conclusions and recommendations were drawn from this study. First, TRIM is an imperfect vehicle for projecting atmospheric deposition impacts because it is a shell which performs the accounting tasks of inventory projection. There is no algorithm in TRIM which simulates, in an analytical sense, atmospheric deposition impacts. Impact quantification must occur exogenously. So TRIM could be used for impact projections once exogenous quantification is accomplished.

Second, regional impact projections may have to be performed using TRIM because it is compatible with existing regional inventory data. There are some alternatives, e.g. TRAS. However, this model is not examined because its regional inventory data are not available.

Modification of growth and/or harvest variables is the most promising for impact projection. This modification is recommended because inventory projections are most sensitive to changes in these variables. Modification of the growth variables requires choosing either the yield table method or the approach-to-normality method.

The yield table method has several advantages. It is the simplest to understand, the simplest to modify, and implicitly assumes a constant stocking level throughout stand life. Only the variable, VOLPA, should be changed to reflect atmospheric deposition impacts if this method is chosen. Since VOLPA is simply the entries in a yield table, yield tables must be re-estimated, exogenously, to reflect atmospheric deposition impacts. A timber production function approach is recommended to extract this exogenous information. Then VOLPA is modified accordingly.

The approach-to-normality method may be used if subsequent biological research indicates that stocking level as well as yield change over time. The variables VOLPA, INTAP, and COEFAP should be changed if this method is chosen. However, use of this method requires additional information about stocking level change, specifically the values for INTAP and COEFAP. There seems to be no *a priori* reason, at this time, why this will provide a better impact estimate than simply changing the yield tables, VOLPA.

Ending inventory is obviously affected by the harvest request, HRVACU, because this is a direct subtraction from the inventory. Theoretically, HRVACU is determined by market forces and so should be estimated using econometric models. HRVACU is unlikely to be directly impacted by atmospheric deposition. The impact will most likely be seen if atmospheric deposition causes a major supply shift which is reflected in price and quantity changes. Linking TRIM to some econometric model seems a promising method of estimating HRVACU.

Table 1. TRIM input data summary.

BRU Input Data:

- Unstocked Acres: total acres
- Donor Acres: acres by donors 1 and 2, and age class
- Timberland Acres: acres and volume per acre by age class, stocking level and mgt. intensity

GRU Input Data:

- BRU's in GRU
- Yield, Thinning and Mortality Tables by Management Intensity
- Acreage Shift Specifications:
  - to and from donors
  - between management options
- Treatment Options:
  - thinning - commercial and precommercial
  - fertilization
- Other Options:
  - regeneration method
  - growth method
  - rational expectation
- Revenue and Cost Data
- Volumetric Conversion Factors

ACU Input Data:

- GRU's in ACU
- Starting Year, Age Class, Period and Simulation Length
- Stocking Level Limits
- Harvest Requests
- Report Requests
- Label Options

Table 2. Initial inventory data categories.

Ownership Category:

- National Forest (NF)
- Other Public (OP)
- Forest Industry (FI)
- Farmer (FM)
- Miscellaneous Private Corporate (MC)
- Miscellaneous Private Individual (MP)

Species Category:

- Natural Pine (NP)
- Pine Plantation (PP)
- Mixed Pine-Hardwoods (OP)
- Upland Hardwoods (UH)
- Bottomland Hardwoods (BH)

Site Category:

- High Site (HIGH)
- Medium Site (MEDIUM)
- Low Site (LOW)

Table 3. Projection for inventory and harvest using the yield table and approach-to-normality methods.

Year	Yield table		Approach-to-normality	
	inventory	harvest	inventory	harvest
		(million cubic feet)		
1985	2308.4	1796.9	2308.4	1796.9
1990	827.0	382.4	1038.2	440.9
1995	594.2	176.3	1063.9	353.5
2000	795.0	156.9	1345.2	310.6
2005	1119.9	305.7	1768.2	588.5
2010	1300.0	537.1	1875.6	735.4
2015	1193.6	324.4	1727.5	448.2
2020	1265.3	294.1	1835.0	490.4
2025	1445.6	568.7	1985.9	797.1
2030	1391.3	718.6	1872.8	984.3
2035	1119.2	608.9	1470.2	785.1

Note: This projection is based on the initial inventory data in Virginia.

Table 4. Inventory projection for each reduction of VOLPA using the yield table method.

Year	Percentage reduction of VOLPA[3]					
	90		80		70	
	MCF[1]	Percent[2]	MCF	Percent	MCF	Percent
1985	2308.4	100	2308.4	100	2308.4	100
1990	771.5	93	708.6	86	643.5	78
1995	567.9	96	515.8	87	464.4	78
2000	745.3	94	670.3	84	593.2	75
2005	1029.1	92	921.1	82	812.2	73
2010	1182.0	91	1055.7	82	929.1	72
2015	1086.9	91	971.8	81	856.2	72
2020	1145.7	91	1024.5	81	900.7	71
2025	1305.6	90	1161.2	80	1015.3	70
2030	1256.8	90	1117.9	80	977.3	70
2035	1006.5	90	895.3	80	782.7	70

1. MCF = Million Cubic Feet.

2. Percent = the ratio of this projection to the baseline projection.

3. VOLPA = the volume per acre in the yield table.

Table 5. Inventory projection for each reduction of VOLPA using the approach-to-normality method.

Year	Percentage reduction of VOLPA[3]					
	90		80		70	
	MCF[1]	Percent[2]	MCF	Percent	MCF	Percent
1985	2308.4	100	2308.4	100	2308.4	100
1990	1018.0	98	997.4	96	977.4	94
1995	1024.5	96	982.9	92	944.0	89
2000	1267.3	94	1185.9	88	1108.8	82
2005	1638.3	93	1504.8	85	1375.7	78
2010	1729.0	92	1578.4	84	1432.6	76
2015	1594.7	92	1457.8	84	1325.8	76
2020	1687.4	92	1535.5	84	1388.8	76
2025	1809.9	91	1631.0	82	1455.7	73
2030	1696.5	90	1519.9	81	1344.0	72
2035	1334.2	90	1197.4	81	1061.7	72

1. MCF = Million Cubic Feet.

2. Percent = the ratio of this projection to the baseline projection.

3. VOLPA = the volume per acre in the yield table.

Table 6. Inventory projection for each reduction of VOLPA, INTAP, and COEFAP using the approach-to-normality method.

Year	Percentage reduction of VOLPA[3], INTAP[4] and COEFAP[5]					
	90		80		70	
	MCF[1]	Percent[2]	MCF	Percent	MCF	Percent
1985	2308.4	100	2308.4	100	2308.4	100
1990	925.9	89	816.1	79	709.4	68
1995	847.5	80	658.8	62	499.5	47
2000	979.0	73	691.5	51	474.9	35
2005	1194.6	68	783.6	44	500.6	28
2010	1207.6	64	757.0	40	464.6	25
2015	1090.4	63	679.7	39	422.6	24
2020	1126.2	61	685.9	37	416.5	23
2025	1219.0	61	744.6	37	451.5	23
2030	1172.8	62	728.1	39	445.6	24
2035	932.1	63	581.8	40	356.2	24

1. MCF = Million Cubic Feet.

2. Percent = the ratio of this projection to the baseline projection.

3. VOLPA = the volume per acre in the yield table.

4. INTAP = the intercept of the approach-to-normality equation.

5. COEFAP = the slope of the approach-to-normality equation.

Table 7. Inventory projection for each reduction of HRVACU using the yield table method.

Year	Percentage reduction of HRVACU[3]					
	50		30		20	
	MCF[1]	Percent[2]	MCF	Percent	MCF	Percent
1985	2308.4	100	2308.4	100	2308.4	100
1990	827.0	100	1362.5	164	1634.7	198
1995	594.2	100	585.3	98	1040.4	175
2000	795.0	100	724.6	91	670.1	84
2005	1119.9	100	1022.0	91	889.8	79
2010	1300.0	100	1217.4	94	1075.8	83
2015	1193.5	100	1339.9	112	1330.1	111
2020	1265.3	100	1233.6	97	1422.0	112
2025	1445.6	100	1370.5	95	1291.8	89
2030	1391.3	100	1393.6	100	1297.7	93
2035	1119.2	100	1160.7	104	1161.7	104

1. MCF = Million Cubic Feet.

2. Percent = the ratio of this projection to the baseline projection.

3. HRVACU = the harvest request.

Table 8. Inventory projection for each level of MINHAR at 4 and 5 using the yield table method.

Year	MINHAR[3] = 4		MINHAR = 5	
	MCF[1]	Percent[2]	MCF	Percent
1985	2308.4	100	2308.4	100
1990	827.0	100	981.0	119
1995	594.2	100	779.5	131
2000	795.0	100	852.0	107
2005	1119.9	100	1105.3	99
2010	1300.0	100	1377.8	106
2015	1193.5	100	1475.7	124
2020	1265.3	100	1432.0	113
2025	1445.6	100	1566.6	108
2030	1391.3	100	1326.5	95
2035	1119.2	100	1202.4	107

1. MCF = Million Cubic Feet.

2. Percent = the ratio of this projection to the baseline projection.

3. MINHAR = the minimum harvest age class.

Chapter 4

TIMBER PRODUCTION FUNCTIONS FOR LOBLOLLY PINE PLANTATIONS

INTRODUCTION

Traditional stand growth and yield models estimate stand volume per acre as a function of stand age, site quality, and stand density. The first stand models for loblolly pine were developed by MacKinney et al. (1937) and Schumacher (1939). Numerous studies subsequently used similar functional forms to predict current volume per acre for loblolly pine stands (e.g. Clutter 1963, Burkhart et al. 1972a, Burkhart et al. 1972b, Amateis et al. 1986). Although useful in predicting timber growth and yield, many stand growth and yield models lack the capability to examine the individual influence of predictor variables on stand growth and yield because of collinearity.

Several studies have shown that estimating timber production functions permits the examination of input-output and input-input relationships and may help foresters prescribe forest management. Nautiyal and Couto (1982) showed the way to use a timber production function in forest management. Later, Rawat and Nautiyal (1985) applied a logarithmic timber production function for economic analysis in intensive forest management. Those results showed that timber production function approaches could be used in intensive forest management for prediction of timber production, control of silvicultural practices, and economic decision making.

Timber production function approaches also could be useful in assessing the environmental impacts on stand growth and yield. Duerr (1979) suggested that biological and environmental factors could be included in timber production function models. Nautiyal and Couto (1984) demonstrated this concept using a polynomial production function to estimate stand growth as a function of stand age, basal area, nutrient, water, and solar radiation available to the tree over the growth period.

Recent studies on stand characteristics suggested that crown variables, which can reflect certain environmental impacts on tree growth, could be an important factor influencing stand growth and yield. Sprinz and Burkhart (1987) examined the relationships between tree crown, stem, and stand characteristics for unthinned stands of planted loblolly pine. Results showed that crown variables are important attributes improving the prediction of stand characteristics. Several studies already incorporated crown ratio into individual tree volume equations (e.g. Burkhart and Walton 1985, Hann et al. 1987). This implied the possibility of developing a timber production function incorporating crown variables.

The distinction between the traditional stand model approach and the timber production function approach lies in the emphasis. The traditional stand model approach emphasizes the accuracy of growth and yield prediction, while the timber production function approach emphasizes the ability to interpret the model's coefficients. Biological rationale, collinearity, and goodness-of-fit are used for both models. However, biological rationale and minimum collinearity are the major criteria in the timber production approach. The selection of functional forms and predictor variables becomes a tradeoff among these criteria.

When remeasurement data are available, compatibility and serial correlation considerations exist. The compatibility between growth and yield requires that the algebraic form of the yield equation could be derived by mathematical integration of the growth equation. Clutter (1963) initiated a compatible growth and yield approach to tackle the compatibility problem. This approach uses a system of yield and basal area equations and solves a derived compatible yield equation. This approach was then used and extended to estimate stand growth and yield for loblolly pine stands (Sullivan and Clutter 1972, Burkhart and Sprinz 1984). Chang (1984) showed a different approach to obtaining compatible stand growth and yield equations using a differentiation and integration method. Using this differentiation and integration method, most stand yield equations can be transformed into a compatible growth equation. Either a yield equation or its compatible growth equation can be used to fit remeasurement data. This approach has some advantages in the flexibility of growth and yield data for fitting stand models.

Serial correlation results if (i) permanent plot data induce serially correlated measurements and (ii) certain coefficients in the yield equation are functionally related to coefficients appearing in predictor equations and residuals from these equations are correlated. The first case of serial correlation might be mitigated using the differentiation and integration method. For the second case, Furnival and Wilson (1971) proposed a three-stage least squares technique to overcome this serial correlation. This technique has been widely used in econometrics for fitting interdependent multiequation models (Judge et al. 1985). Recently, this three-stage least squares technique was used to fit systems of forest growth and yield models (Murphy and Sternitzke 1979, Murphy and Beltz 1981, Borders and Bailey 1986). Another technique, seemingly unrelated regressions (Zellner 1962), was used by Murphy (1983) to fit a yield equation system for loblolly pine. Those results indicated that the simultaneous equation techniques could retain the advantage of the compatible growth and yield approach while providing more efficient estimates.

When examining input-output and input-input relationships, e.g. various elasticities, from timber production functions, one needs to diagnose the existence of collinearity among predictor variables.

Multiple correlation of one input variable regressed on the remaining variables is used to diagnose collinearity (Belsley et al. 1980). Collinearity exists if there is a high multiple correlation. Collinearity can cause computational problems since solutions to a set of least-squares normal equations are very sensitive to changes in the data set if collinearity is present. Also, collinearity can reduce the precision of statistical estimates because the conditional variances are high. Therefore, if collinear variables exist, it becomes difficult to infer the separate effect of such input variables on the output. Two measures of collinearity, condition number and variance inflation factor, were used to detect collinearity in this study.

OBJECTIVES

The objectives of this study were three-fold. First, to develop a loblolly pine timber production function including crown variables using the differentiation and integration method and a system of predictor equations for the yield equation. Second, to examine the corresponding input-input and input-output relationships. Finally, to use the timber production function for assessing the impacts of environment and silvicultural and management practices on stand growth and yield.

MODEL DEVELOPMENT

Following the basic form of Schumacher's yield model (Schumacher 1939), this study hypothesized that the logarithm of stand yield is a function of the reciprocal of stand age and some measures of site quality, stand density, and crown size. Site quality is a measure of the productive capacity of the environment; it has been measured in a variety of ways. This study selected site index, or average dominant stand height at an index age as the measure of site quality since these two site variables are available in the data set.

Stand density is a quantitative measure of crowding of stems within a stand. Measures of stand density include basal area per acre, number of trees per acre, stand density index, and crown competition factor. Burkhart et al. (1982) pointed out that for yield prediction purposes the crown competition factor and stand density index did not appear to offer any advantage over basal area per acre and number of trees per acre. So, basal area per acre or number of trees per acre was used in this study as a measure of stand density.

Crown size exhibits the internal mechanisms and the cause and effect relationships of how crown development influences stem development. Crown size can be measured by crown length, crown ratio, crown diameter, and/or crown projection area. Crown ratio or crown length was chosen in this study based on empirical results and ease of interpretation.

YIELD EQUATIONS

Based on Schumacher's yield model, the general form for the timber production function is proposed as:

$$log(V) = a_0 + a_1\left(\frac{1}{A}\right) + a_2 f(SD) + a_3 g(SQ) + a_4 h(CS) \qquad [1]$$

where $\log(V)$ = the natural logarithm of volume per acre in cubic feet
A = the stand age
$f(SD)$ = the function of stand density
$g(SQ)$ = the function of site quality
$h(CS)$ = the function of crown size
a_0, a_1, a_2, a_3, a_4 = parameters to be estimated

The functional forms for the stand density, site quality, and crown size variables could be a logarithm, reciprocal, or simple form. The general relationships between stand volume and age, site quality, stand density, and crown size are well known. Since stands of trees are biological systems, measures of stand volume exhibit the common sigmoid curve shape when plotted over age. The sign for the coefficient of the reciprocal of age should be negative.

In all stands of trees, stand density increases until it approaches an asymptote which represents the biological carrying capacity. The sign for the stand density coefficient is expected to be positive. In most cases, trees grow more rapidly on better sites. The volume per acre will be larger if the associated site is better, given the same stand age and density. The sign for the coefficient of site quality is assumed to be positive. Studies on stand characteristics suggested that trees of a given diameter at breast height and total height with large crown size generally had greater volume. The development of dominant stand height follows a similar trend. So the coefficient of crown size should have a positive sign.

In order to develop a compatible growth equation, the differentiation and integration method was used. Taking the derivative of Equation [1] with respective to stand age, we obtain:

$$\frac{(dV/dA)}{V} = -a_1(A^{-2}) + a_2(dSD/dA)f'(SD) + a_3(dSQ/dA)g'(SQ) + a_4(dCS/dA)h'(CS)$$

where $f'(SD)$, $g'(SQ)$, and $h'(CS)$ are the derivatives of $f(SD)$, $g(SQ)$, and $h(CS)$, respectively. This is a separable linear differential equation. Given some initial condition at age A_0, the solution to this differential equation gives:

$$\log(\frac{V}{V_0}) = a_1(\frac{1}{A} - \frac{1}{A_0}) + a_2(f(SD) - f(SD_0)) + a_3(g(SQ) - g(SQ_0)) + a_4(h(CS) - h(CS_0)) \quad [2]$$

where V_0, A_0, SD_0, SQ_0, and CS_0 are the initial conditions for the volume per acre, stand age, stand density, site quality, and crown size, respectively. Equations [1] and [2] are compatible growth and yield equations in that the coefficients can be estimated either by equation [1] or by equation [2] depending on the nature of the growth data set.

The possible functional forms for the stand density, site quality, and crown size variables can be a simple, reciprocal, or logarithmic form. Combinations of each possible case form many possible yield equations. The t-value and sign criteria were used to select the possible functional forms for the yield equation. After screening many possible yield equations, three possible functional forms for the timber production model [1] were chosen to fit the data set. These three equations are:

$$log(V) = a_0 + a_1(\frac{1}{A}) + a_2 \log(SD) + a_3 SQ + a_4 CS \qquad [3]$$

$$log(V) = a_0 + a_1(\frac{1}{A}) + a_2 SD + a_3(\frac{1}{SQ}) + a_4 CS \qquad [4]$$

and

$$log(V) = a_0 + a_1(\frac{1}{A}) + a_2 \log(SD) + a_3 \log(SQ) + a_4 CS \qquad [5]$$

Then the corresponding compatible growth equations are derived as:

$$log(\frac{V}{V_0}) = a_1(\frac{1}{A} - \frac{1}{A_0}) + a_2(\log(SD) - \log(SD_0)) + a_3(SQ - SQ_0) + a_4(CS - CS_0) \qquad [6]$$

$$log(\frac{V}{V_0}) = a_1(\frac{1}{A} - \frac{1}{A_0}) + a_2(SD - SD_0) + a_3(\frac{1}{SQ} - \frac{1}{SQ_0}) + a_4(CS - CS_0) \qquad [7]$$

and

$$log(\frac{V}{V_0}) = a_1(\frac{1}{A} - \frac{1}{A_0}) + a_2(\log(SD) - \log(SD_0)) + a_3(SQ - SQ_0) + a_4(CS - CS_0) \qquad [8]$$

Since the reciprocal of site quality should have an inverse relation with volume per acre, the corresponding sign is expected to be negative in equation [4].

Among these equations, more than one observed variable can be used to represent stand density, site quality, and crown size. For example, basal area per acre and number of trees per acre can represent stand density, site index and dominant height as site quality, and crown length and crown ratio as crown size.

Equation [2] can be rearranged as:

$$V = V_0 \exp(a_1(\frac{1}{A} - \frac{1}{A_0}) + a_2(f(SD) - f(SD_0)) + a_3(g(SQ) - g(SQ_0)) + a_4(h(CS) - h(CS_0))) \quad [9]$$

Equation [9] is a stand yield projection model in which the future timber production can be estimated, given the initial conditions and the projected stand density, site quality, and crown size for the stand of interest. So, stand density, site quality, and crown size models must be added to the system in order to project future volume. A review of stand density, site quality, and crown size models suggested the following approaches to developing functional forms for projecting each of these predictor variables.

STAND DENSITY MODELS

The form of stand density models depends on the variable used. If basal area per acre is selected as the stand density variable, then the basal area projection model will be needed for the equation system. Otherwise, if number of trees per acre is selected, a mortality function should be used for the equation system.

Clutter (1963) developed a basal area projection model, assuming that basal area is a function of stand age, site quality, and initial basal area. Clutter's basal area projection model was used in several systems of stand models (e.g. Sullivan and Clutter 1972, Burkhart and Sprinz 1984). Bennett's (1970) basal area projection model expressed future basal area as a function of current stand age and basal area, and future stand age, ignoring site quality. Borders and Bailey (1986) assumed that the future basal area is a function of current basal area and dominant height and future dominant height. Gregoire (1987) developed another basal area model as a function of stand age and average dominant height. Those results suggested that the future basal area could be a function of initial basal area, stand age and dominant height, and future stand age and dominant height.

Based on the above assumption, a new functional form for the basal area projection model is:

$$B = e^{(A_0/A)logB_0 + b_1(1 - A_0/A) + b_2(1 - Hd_0/Hd)} \qquad [10]$$

This projection equation implies that when stand age approaches A_0 and dominant height approaches Hd_0, then basal area per acre approaches B_0. Also, when stands grow older, basal area per acre approaches an asymptote, $e^{b_1 + b_2}$.

SITE QUALITY MODELS

Site quality models could be dominant height equations or site index equations. The development of site index equations is equivalent to the development of dominant height equations. Site index equations predict site quality from stand age and dominant height information.

The general progression of average dominant height through time is quite consistent and generally sigmoidal. The height growth is slow at the seedling stage, most rapid at the sapling and pole stages, and decelerated in the thrifty-mature stage. Schumacher (1939) developed a well known logarithm height-reciprocal of age model. This model has been widely used to fit site index curves. Bailey (1980) used a Weibull-type function for the height equation and compared it with other height equations. Bailey pointed out that Schumacher's model seemed better for young stands.

A new functional form for the dominant height model was used. This function form is similar to Schumacher's model but it is assumed that the logarithm of dominant height is proportional to the exponential of the reciprocal of stand age. That is,

$$log(Hd) = c_1 e^{c_2(1/A)} \qquad [11]$$

The corresponding site index equation is then given as:

$$log(SI) = \log(Hd)(\frac{\exp(c_2(1/A_0))}{\exp(c_2(1/A))}) \quad [12]$$

Equation [11] implies that the average dominant height equals unity at the beginning of planting. This implication is not unreasonable for loblolly pine plantations. Also, Equation [11] can be used to derive a dominant height projection equation using differential and integration methods. The dominant height projection equation is then given as:

$$Hd = Hd_0 \exp(c_1(e^{c_2/A} - e^{c_2/A_0})) \quad [13]$$

This dominant height projection equation can be used with yield equations to project future yield.

CROWN SIZE MODELS

Crown size models can be represented by either crown length models or crown ratio models. Tree crown length is the length of live crown from bottom to tip, while tree crown ratio is the ratio of live crown length divided by total tree height. Although individual tree crown length and crown ratio are compatible, averaged stand crown length and crown ratio are not. However, if one of these two models is developed, then we can apply this functional relationship for the other. So, the development of a crown length model is similar to the development of crown ratio model.

Studies on stand characteristics indicated that individual tree crown ratio decreased with increasing total tree height or stand density (Harms and Langdon 1976, Sprinz and Burkhart 1987). Dyer and Burkhart (1987) developed individual tree crown ratio and crown height models assuming that (i) trees with more taper have higher crown ratios than those trees with less taper; and (ii) crown ratio will decrease with age and the rate of this decrease will level off with time. Holdaway (1986) developed a different crown ratio model assuming that tree crown ratio is a function of basal area and diameter at breast height. Holdaway hypothesized that the main factor related to tree crown ratio was competition for light from surrounding forest and a second factor was the tree's ability to compete due to its degree of dominance.

For stand level crown ratio models, Holdaway's hypothesis seems to be more suitable in describing the development of crown ratio. The development of stand crown length is assumed to be inversely related to the stand density and directly related to the dominant height.

Following this hypothesis, a new functional form for the crown ratio is given by:

$$Cr = \frac{d_1}{1 + d_2 B} + d_3(1 - e^{d_4(Hd-4.5)}) \tag{14}$$

Where the value of 4.5 in this equation indicates the breast height. Then the crown length model is derived as:

$$Cl = \frac{d_1 Hd}{1 + d_2 B} + d_3 Hd(1 - e^{d_4(Hd-4.5)}) \tag{15}$$

Equation [14] implies that crown length approaches dominant height when dominant height equals breast height and so basal area approaches zero, providing d_1 is near unity.

METHODS

Ordinary least squares (OLS), three-stage least squares (3SLS), and seemingly unrelated regressions (SUR) were respectively applied to fit this system of equations. The selection of coefficient estimates from these techniques was based on efficiency and precision of estimation. At least three criteria were used to choose the variables for stand density, site quality, and crown size, and the functional forms for the system of equations. These criteria were (1) goodness-of-fit, (2) minimal collinearity, and (3) consistency of sign for parameters.

The goodness-of-fit criterion is examined by fit index (FI), mean difference (MD), standard error (SE), and t-value. The higher the value for fit index or the lower the value for mean difference or standard error, the better the equation fitted. Also, models with coefficient t-values not significant at the 5 percent level were rejected.

Collinearity among the input variables is often examined using (i) the eigenvalues and eigenvectors of the input variable correlation matrix, and (ii) the multiple correlation between pairs of input variables (Mansfield and Helms 1982). The ratio of maximal to minimal eigenvalues is the condition number (CN) and is a measure of the sensitivity of least squares estimates to minor perturbation of the input data. As a simple rule of thumb, if the condition number does not exceed 100, we can conclude that the estimates by OLS are not sensitive to the minor perturbation of the input data.

The variance inflation factor (VIF) is the inverse of unity minus the multiple correlation coefficient of one input variable that is regressed on the remaining input variables. It measures the effects of collinearity on the variances of the input variable. If the VIF's for some input variables are not unusually larger than 1.0, then the variance of coefficient estimates are not affected by collinearity. The standard error and t-value for each parameter can also be used to signal the existence of collinearity. The higher the t-value or the lower the standard error, the more stable the coefficient estimates.

Growth data from light-thinned and heavy-thinned stands were used to test the precision in projecting stand dynamics. Given that the volume per acre, basal area per acre, and dominant height after thinning are the initial conditions, the basal area and dominant height projection equations are used to project the future basal area and dominant height. The crown length model is used to estimate the crown length at any age. Then the yield projection equation is used to project the future volume per acre based on the above information. Mean difference (MD) and standard deviation of the differences between observed and projected values were used to judge this projection. Also, the projection of stand dynamics by the equation system without crown length was made to compare the above projection. Finally, various elasticities, including cross partial derivatives, partial elasticities, elasticity of scale, and elasticities of substitution, were calculated to examine the input-output and input-input relationships.

DATA

The data used in this study are from loblolly pine plantations located in the Southeastern United States (see Burkhart et al. 1985 for a detail description of the data). During 1981 and 1982 dormant seasons, permanent plots were established in cutover, site-prepared plantations. Remeasurement data were collected 3 years later. Measurement data from the plots were used to compute volume per acre, basal area per acre, dominant height, crown ratio, crown length, and number of trees per acre.

Table 9 shows summary statistics for the 171 sample plots. Amateis and Burkhart's (1987) equation was used for computing individual tree volume in cubic feet. The volume per acre (ft^3/acre) is the sum of merchantable individual tree volume for loblolly pine on the plots. Basal area per acre (ft^2/acre) is the total overstory basal area. Dominant height in feet is the arithmetic mean height of dominant and codominant trees of loblolly pine. Individual tree crown ratio is defined as the ratio of the live crown length to the total tree height. The value for crown ratio used in the system of equations is the arithmetic mean crown ratio of loblolly pine trees. Crown length in feet is the average length of the live crown for loblolly pine. The number of trees per acre is the total of overstory trees.

RESULTS

MODEL ESTIMATION

Final selection of the yield equation and predictor variables using the criteria given is:

$$log(\frac{V}{V_0}) = a_1(\frac{1}{A} - \frac{1}{A_0}) + a_2(B - B_0) + a_3(\frac{1}{SI} - \frac{1}{SI_0}) + a_4(Cl - Cl_0) \qquad [16]$$

where B = the basal area per acre ($ft^2/acre$)
SI = the site index based on age 25
Cl = the average crown length in feet
a_1, a_2, a_3, a_4 = coefficient estimates

The basal area per acre can be projected by Equation [10], given that the dominant height is known. The dominant height can be projected by Equation [13] for any stand age. The site index is estimated by Equation [12]. And the crown length can be estimated by Equation [15], given that basal area per acre and dominant height are known. Thus, Equations [10], [12], [13], [15], and [16] constitute a system of equations with which one can project the future volume per acre, basal area per acre, and dominant height at any stand age for loblolly pine plantations, once the initial conditions for stand age, basal area per acre, volume per acre, and dominant height are known.

Initially, equations [10], [11], [13], [15], and [16] were fitted separately by OLS. Table 10 contains the information for the OLS coefficient estimates and the corresponding standard errors and t-values. All coefficient estimates are significantly different from zero at the 5 percent level. This means that all the predictor variables could have a significant contribution to the variation of the output variable. The signs associated with each predictor variable are consistent with biological knowledge, which implies that these input variables have good predictability.

Fit index (FI), mean difference (MD), and standard error (SE) of the differences between observed and projected values were used to examine the goodness-of-fit performance for this system of equations. Table 11 provides this information. The high fit index implies that the predictor variables contribute a large percentage of variation in the output variable. Only the crown length model exhibits a poor fit index, probably due to the small variability of crown length data between measurements. The mean difference indicates that predicted volumes and basal area are slightly over-estimated, while predicted dominant height and crown length are slightly under-estimated. The relatively small standard error, compared to the mean value statistics, implies that all these equations may have good extrapolation properties.

Ordinary least squares (OLS) might not be appropriate to estimate the parameters of the equation system because the residuals from each equation are probably cross-correlated. For instance, the basal area and crown length variables are independent in the yield equation but dependent in their own equation. Econometric studies have developed techniques to produce efficient estimators. These techniques include three-stage least squares (3SLS) and seemingly unrelated regressions (SUR). Both these two techniques were used to fit this system of equations. In order to efficiently utilize the data, this equation system was revised as:

$$log(\frac{V}{V_0}) = a_1(\frac{1}{A} - \frac{1}{A_0}) + a_2(B - B_0) + a_3(\frac{1}{SI} - \frac{1}{SI_0}) + a_4(Cl - Cl_0)$$

$$B = e^{(A_0/A)logB_0 + b_1(1 - A_0/A) + b_2(1 - Hd_0/Hd)}$$

$$Hd = Hd_0 \exp(c_1(e^{c_2/A} - e^{c_2/A_0}))$$

$$Cl_1 = \frac{d_1 Hd_1}{1 + d_2 B_1} + d_3 Hd_1(1 - e^{d_4(Hd_1 - 4.5)})$$

$$Cl_2 = \frac{d_1 Hd_2}{1 + d_2 B_2} + d_3 Hd_2(1 - e^{d_4(Hd_2 - 4.5)})$$

The first crown length equation was fitted with the first measurement data, while the second crown length equation was fitted with the remeasurement data. This revised equation system were fitted by nonlinear SUR and 3SLS in SAS/ETS (SAS Institute 1984).

Table 12 provides the information for the SUR and 3SLS coefficient estimates and the corresponding standard errors and t-values. All the coefficient estimates are significant at the 5 percent level and the signs are consistent. The values for the SUR and 3SLS coefficient estimates, standard errors, and t-values are not much different from each other. In general, the SUR estimates have higher t-values than the 3SLS and OLS estimates. This suggests that the SUR estimates are more stable and efficient than the OLS and 3SLS estimators. Table 13 provides the information for the goodness-of-fit performance using SUR and 3SLS. The values for fit index, mean difference, and standard error suggest that the SUR coefficient estimates have a similar level of goodness-of-fit and precision as the OLS and 3SLS estimates.

The condition number (CN) in Table 14 signals that the OLS coefficient estimates are not sensitive to minor perturbations in the input data. The VIF's for the site index and crown length variables indicate that the variances of the corresponding coefficient estimates are not affected by collinearity. For stand age and basal area variables, the relatively large VIF's indicate that the variances of these OLS coefficient estimates could be affected by collinearity.

The collinearity problem may be ameliorated when the equation system is fitted by SUR. As shown above, the standard errors become smaller and the t-values larger if fitted by SUR. This indicates that the variances of most SUR coefficient estimates are reduced and the coefficient estimates are more stable. When one wishes to use equations to examine the input-input and input-output relationships, the SUR coefficient estimates might be better for giving the individual effects on the output variable. Therefore, the SUR coefficient estimates were used for the analysis of elasticities.

Most thinning studies concluded that thinning did not significantly affect total volume productivity per acre. However, thinning might affect the development of crown size and breast height diameter, which in turn might affect the future stand growth. Equations [10], [13], [15], and [16] implicitly take into account the thinning effect on stand growth and yield. Once a stand is thinned and basal area is reduced, then the future basal area and crown length will differ from those unthinned stands with the same basal area and crown length. Therefore, the projected volume per acre would be different.

Growth data from light-thinned and heavy-thinned plantations were used to evaluate the capability to project stand dynamics with coefficient estimates by OLS, SUR, and 3SLS. The thinning intensity averaged 29 percent of the initial basal area removed for light-thinned plots and 43 percent removed for heavy-thinned plots. Given that the volume per acre, basal area per acre, and dominant height after thinning are the initial conditions, the basal area and dominant height projection equations are used to project the future basal area and dominant height. The crown length model is used to estimate the crown length at any age. Then the yield projection equation is used to project the future volume per acre based on the above information. Mean difference (MD) and standard deviation of the differences between observed and projected values were used to judge the projection. Table 15 shows that the coefficient estimates by OLS, SUR, and 3SLS give a slightly higher value for mean difference and standard deviation, compared with the values in Tables 11 and 13.

The positive mean difference values in Table 15 suggests that the projected volume per acre for thinned stands is slightly under-estimated by this system of equations. The relative mean difference between observed and estimated values are 0.96 and 2.58 percent of mean volume for light-thinned and heavy-thinned stands respectively. If this equation system can reflect the development of unthinned stands, the thinned stands might grow faster than unthinned stands with the same initial values of the predictor variables. Although the values for standard deviation are not as good as those in Tables 11 and 13, the relative precision is still high. So, this system of equations can be used to project stand dynamics for loblolly pine plantations with an acceptable error.

The system of equations without crown length was fitted with the same growth data using OLS, SUR, and 3SLS. Table 16 shows this estimation. These coefficient estimates were used to project volume per acre for the thinned stands. Table 17 shows that these coefficient estimates without crown length have higher precision than those with crown length in projecting thinned stands. The inclusion of the crown length variable might increase the corresponding variance in the yield equation because of the compound problem.

ELASTICITIES

Many relationships between output and an input or between pairs of inputs can be derived from a production function (Beattie and Taylor 1985). These relationships can be used to characterize several properties of the timber production process, such as marginal and average physical products, factor interdependence, various elasticities, and rates of substitution. The most important properties for economic purposes are the technical interrelationships, the partial elasticities of output with respect to each input factor and the elasticities of substitution between the inputs. This information can be useful for examining the functional form for the production process and for guiding forest managers in prescribing management practices.

The technical interrelationship between factors of production can be examined by the marginal productivity of input variables. For instance, two factors are technically independent if the marginal productivity of one is not a function of the other factor. Given a production function, there are three types of technical interrelationships. If the cross partial derivative of output with respect to the two inputs is greater than zero, then these two inputs are technically complementary. Otherwise, these two inputs are technically competitive for the cross partial derivative less than zero and technically independent for the cross partial derivative equal zero. The measures of factor interdependence are given as follows.

(1) cross partial derivative with respect to age and basal area at the mean values:

$$\frac{\partial^2 V}{\partial A \partial B} = -a_1 a_2 V A^{-2} = 0.0833 V A^{-2} = 0.7603$$

(2) cross partial derivative with respect to age and site index at the mean values:

$$\frac{\partial^2 V}{\partial A \partial SI} = a_1 a_3 V A^{-2} SI^{-2} = 861.2341 V A^{-2} SI^{-2} = 2.2506$$

(3) cross partial derivative with respect to age and crown length at the mean values:

$$\frac{\partial^2 V}{\partial A \partial Cl} = -a_1 a_4 V A^{-2} = 0.1110 V A^{-2} = 0.9871$$

(4) cross partial derivative with respect to basal area and site index at the mean values:

$$\frac{\partial^2 V}{\partial B \partial SI} = -a_2 a_3 V SI^{-2} = 0.2381 V SI^{-2} = 0.1808$$

(5) cross partial derivative with respect to basal area and crown length at the mean values:

$$\frac{\partial^2 V}{\partial B \partial Cl} = a_2 a_4 V = 0.00003 V = 0.0796$$

(6) cross partial derivative with respect to site index and crown length at the mean values:

$$\frac{\partial^2 V}{\partial SI \partial Cl} = -a_3 a_4 V SI^{-2} = 0.3175 V SI^{-2} = 0.2412$$

Since all the cross partial derivatives are positive, all the input variables should be everywhere technically complementary for the timber production process. Also, the corresponding ridge lines are positively sloped and linear with a global maximum for any positive input variable. For example, if the time to grow timber is longer, then the basal area and crown length will be larger. This relationship is consistent with *a priori* biological knowledge. So, the fitted yield equation that imposes a complementary factor interdependence can reasonably represent the timber production process. Also, the value of cross partial derivative signals the degree of interdependence. The interdependence between age and site index is the strongest, while this relationship between basal area and crown length is the least.

The partial elasticities of timber output with respect to each input factor provide a measure of their individual contribution to the timber production process. For instance, the partial elasticity of stand volume with respect to age tells the percentage change in volume for a one percent change in age, holding all other factors fixed. The elasticity of scale provides information about the percentage change in volume due to a simultaneous one percent change in age, basal area, site index, and crown length. These elasticities are:

(7) partial elasticity with respect to stand age:

$$E_{(V,A)} = (\frac{\partial V}{\partial A})(\frac{A}{V}) = a_1 A^{-1} = 17.3589A^{-1}$$

(8) partial elasticity with respect to basal area:

$$E_{(V,B)} = (\frac{\partial V}{\partial B})(\frac{B}{V}) = a_2 B = 0.0048B$$

(9) partial elasticity with respect to site index:

$$E_{(V,SI)} = (\frac{\partial V}{\partial SI})(\frac{SI}{V}) = a_3 SI^{-1} = 49.6134SI^{-1}$$

(10) partial elasticity with respect to crown length:

$$E_{(V,Cl)} = (\frac{\partial V}{\partial Cl})(\frac{Cl}{V}) = a_4 Cl = 0.0063Cl$$

(11) elasticity of scale:

$$E = E_{(V,A)} + E_{(V,B)} + E_{(V,SI)} + E_{(V,Cl)} = 17.3589A^{-1} + 0.0048B + 49.6134SI^{-1} + 0.0063Cl$$

The partial elasticity of volume with respect to age indicates that the proportion growth ($\partial V/V$) for the proportion increase in age ($\partial A/A$) depends on the stand age, holding all other factors fixed. This relative growth decreases with age. Since the culmination of mean annual increment occurs at the age where the current annual increment ($\partial V/\partial A$) equals the mean annual increment (V/A), the value for the elasticity suggests that the age of maximum mean annual increment is about 17 years. This value is a little short for loblolly pine. This elasticity has considerable management significance if the corresponding variance inflation factor shows no collinearity problem. For a forest owner whose objective is to maximize volume productivity per acre over time, the rotation age used should be the rotation of maximum mean annual increment, i.e. 17 years. Since the corresponding VIF shows that collinearity might create large variance for this coefficient, this value becomes less significant in management decisions.

The partial elasticity with respect to basal area depends on the density of stands, holding all other factors fixed. The value for this elasticity indicates that the relative growth rate increases with stand density. The increase of volume per acre is a function of current volume per acre, current basal area per acre, and the relative increase of basal area per acre. That is, $\partial V = 0.0048VB(\partial B/B)$. So, if the current basal area per acre is 114.76 ft^2/acre, then 10 percent increase in basal area can result in an increase of 13.45 ft^3/acre for a stand with 2345.98 ft^3/acre. However, this is not always the case for a dense stand. Also, the corresponding VIF is high and suggests that this quantitative information might be less accurate.

The partial elasticity with respect to site index depends on how good a site is, holding all other factors fixed. The positive value suggests that the improvement of site quality can increase the productivity of the stand. The increase of productivity decreases with site quality. For instance, the changes in growth for a one percent increase on a stand with 50 feet site index is twice as large as that on a stand with 100 feet site index, given all other factors are the same.

The partial elasticity with respect to crown length indicates that the percentage change in growth for a one percent change in crown length depends on the current crown length, holding all other factors fixed. The positive value implies that the bigger the crown length, the larger the potential vigor for the stand. Since crown length is directly related to photosynthesis potential of trees, the anabolic growth rate might be larger for a bigger crown size. If a one percent increase in crown length is expected, then the stand will increase ($0.00063VCl$) amount of volume in the near future, where V and Cl are the current volume per acre and crown length. Conversely, if the crown length is reduced by one percent, then the stand will lose the same amount of growth. This information can be used to assess environmental impacts on stand growth, if the development of crown size is known to be affected by some environmental factors. Recent studies on forest decline suggested that atmospheric deposition might cause growth loss, mortality, and foliage damage of trees. Crown size development is vulnerable to atmospheric deposition. So varying crown size could be used to indicate the possible level of atmospheric deposition.

The elasticity of scale is the total of all individual elasticities. The value of the elasticity of scale suggests that the total growth rate depends on current age, basal area, site index, and crown length. For example, the changes in growth for a one percent increase on stand age, basal area, site index, and crown length equal 2.9 percent for the first measurement data and 2.7 percent for the second measurement data. The relative growth increases with stand density and crown length and decreases with age and site index. In a young stand, this relative growth is more sensitive to age and site index than to basal area and crown length. When stands grow older, basal area and crown length become relatively important. On average, the value of this elasticity of scale decreases with stand age.

There are two different definitions for the elasticity of substitution between pairs of input variables. One is to characterize the curvature of the isoquants for particular combinations of these input variables (Beattie and Taylor 1985). The other is to characterize the slope of the isoquants for particular combinations of these input variables (Heady 1952). An isoquant is a curve of combinations of two inputs yielding a constant output. The curvature of an isoquant is the rate of change in the slope of this isoquant. The slope of an isoquant is more visible than the curvature. For ease of interpretation, this study follows Heady's definition and the elasticity of substitution between two input variables is defined as the ratio of relative changes in both input factors required along an isoquant. It estimates the trade-off necessary between inputs to keep production constant. The elasticities of substitution are

(12) elasticity of substitution between age and basal area:

$$E_{(A,B)} = -\left(\frac{\partial A}{\partial B}\right)\left(\frac{B}{A}\right) = -\left(\frac{a_2}{a_1}\right)AB = -0.0003AB$$

(13) elasticity of substitution between age and site index:

$$E_{(A,SI)} = -\left(\frac{\partial A}{\partial SI}\right)\left(\frac{SI}{A}\right) = -\left(\frac{a_3}{a_1}\right)ASI^{-1} = -2.8581ASI^{-1}$$

(14) elasticity of substitution between age and crown length:

$$E_{(A,Cl)} = -\left(\frac{\partial A}{\partial Cl}\right)\left(\frac{Cl}{A}\right) = -\left(\frac{a_4}{a_1}\right)ACl = -0.0004ACl$$

(15) elasticity of substitution between basal area and site index:

$$E_{(B,SI)} = -\left(\frac{\partial B}{\partial SI}\right)\left(\frac{SI}{B}\right) = -\left(\frac{a_3}{a_2}\right)B^{-1}SI^{-1} = -10336.125B^{-1}SI^{-1}$$

(16) elasticity of substitution between basal area and crown length:

$$E_{(B,Cl)} = -\left(\frac{\partial B}{\partial Cl}\right)\left(\frac{Cl}{B}\right) = -\left(\frac{a_4}{a_2}\right)B^{-1}Cl = -1.333B^{-1}Cl$$

(17) elasticity of substitution between site index and crown length:

$$E_{(SI,Cl)} = -\left(\frac{\partial SI}{\partial Cl}\right)\left(\frac{Cl}{SI}\right) = -\left(\frac{a_4}{a_3}\right)SICl = -0.0001SICl$$

The elasticity of substitution between age and basal area indicates that stands with less density take more growth time to maintain the same volume per acre. Since stand density measures the extent to which the innate productive capacity has been fully utilized, it is reasonable that the less the stand density, the slower the stand will grow. Also, it implies that it takes longer to reach the maximum carrying capacity for stands with less density. The ease of the substitution depends on the current stand age and density. When stands grow older, this substitution becomes easier.

The elasticity of substitution between age and site index indicates that poor sites require a longer growth period to maintain the same volume per acre. Since the site of a stand involves the totality of environmental conditions, stand productivity at various ages is partially controlled by site quality. So, poor sites always provide a poorer growth condition. Also, it takes longer to reach the maximum mean annual increment for poor sites. The ease of substitution depends on the current age and site quality. When site quality is improved on a stand, the benefit might be shorter in older stands than in younger stands. Fertilizer application is one example of site quality improvement.

The elasticity of substitution between age and crown length indicates that stands with shorter crown length require a longer growth period to maintain equal volume per acre. Since shorter crown length usually provides a slower anabolic growth rate, provided that no changes in crown shape are considered, it takes longer time to reach the maximum mean annual increment. However, the value of the elasticity implies that this substitution is not easy. More time is needed for shorter crown length stands to reach the same volume per acre as longer crown length stands. So to maintain longer crown length for a stand is very important for this stand's productivity.

The elasticity of substitution between basal area and site index indicates that poor sites require dense stands to maintain equal productivity. This suggests that the responses to different thinning practices might be great among stands with different site quality. So, different intensities of thinning should be applied to different sites. On poor sites, one needs to keep more basal area to maintain the same productivity, so thinning can not be heavy.

The elasticity of substitution between basal area and crown length indicates that stands with less density need longer crown length to maintain equal productivity. When the innate productive capacity has not been fully utilized, the anabolic growth rate can be increased with crown length. If thinning, pruning, irrigation, or fertilization affect crown size development, then stand productivity can be improved by those practices. Also, since crown size can reflect the environmental impacts, those practices sometimes can ameliorate the environmental pollution if it exists.

The elasticity of substitution between site index and crown length indicates that poor sites require bigger crown length to keep the productivity the same. This implies that the productivity of stands with poor site quality can be improved by genetic species having larger crown length. Pruning is not applicable on a poor site. Also, crown size becomes relatively more important on poor sites than on good sites. So, stands on poor sites are probably more vulnerable to pollutants than on good sites.

DISCUSSION AND SUMMARY

By a timber production function approach, the basic form of Schumacher's model (1939) was used to describe the timber production process. By incorporating the crown length variable, this timber production function can be used to examine the relationship between crown length and stand growth and yield, stand density, and site quality. Many forest decline studies have revealed that tree foliage is vulnerable to certain types of atmospheric deposition. Therefore, crown size changes may be used to simulate certain environmental impacts on stands. However, the quantitative relationship between crown size and atmospheric deposition is yet to be studied so this model can only be used for sensitivity analysis. Despite this deficiency, this timber production function initiates the study to incorporate biological factors in stand models. The benefit of this effort not only enhances the capability of stand models for describing the stand growth process, but can also extend the use of stand models to examine the individual influence of site index and crown length variables on timber output.

When remeasurement data are available, a compatible growth and yield equation approach has been used to develop a system of stand models. Different types of compatible growth and yield equations are derived using differentiation and integration methods. Several merits were found using the differentiation and integration method to model stand growth and yield. First, the use of the difference of logarithmic yield as the compatible growth can reduce the serial correlation from permanent plot data and provide the capability of including some time-series environmental variables if periodic environmental data are available. Second, collinearity can be reduced to some extent. The collinearity problem has not received such strong emphasis in the traditional stand model approach. When the information about individual influence of input factors on stand growth and yield is needed, the differentiation and integration method becomes appealing. Third, more degrees of freedom are available from observed data when the number of remeasurements exceeds three. Actually, the increase will be in a Fibonacci series. Finally, basal area and dominant height models can apply this differentiation and integration method to derive a projection equation form. As shown above in the system of equations, basal area and dominant height models exhibit a high fit index since both models are in the form of projection equations. It is not coincident because projection equations can always utilize the initial information if given. In most cases, we can obtain the current status of stands, so the use of projection equations is feasible.

The cross partial derivative shows that the functional form used in the yield equation is consistent with the presumed timber production process. The variance inflation factor indicates that site index and crown length variables have no collinearity problem, while stand age and basal area variables are probably affected. So this timber production function can be used to infer the input-output and input-input relationships for site index and crown length variables. The quantitative measures of the input-output and input-input relationships for age and basal area variables are less reliable.

The rotation of maximum mean annual increment can be derived from a timber production function if the age variable was not affected by collinearity. The developed timber production function suggests that 17 years might be the rotation of maximum mean annual increment for total cubic-foot volume production. This figure is under-estimated but close to the rotation age commonly used in loblolly pine plantations. This less reliable estimation results because (i) the stand age variable might be affected by collinearity; (ii) this figure does not take into account the stand density, site quality, and crown size factors; and (iii) the measurement data are taken from stands with age of fast growth. As shown above, stands with less density, poor quality, or small crown size might have a longer rotation age.

From the crown length elasticity, one can extract the individual influence of crown length on stand growth and yield. This information is important when one tries to measure a quantitative effect of environment on stand growth and yield. From the site index elasticity, one can obtain the separate effect of site quality improvement on stand growth and yield. This information is useful for assessing the benefit of silvicultural practices on increasing site index. In summary, the results from the input-output and input-input relationships not only clarify some conventional wisdom in forest management, but further provide some insight into how these predictor variables interact.

OLS, SUR, and 3SLS were applied to fit this system of equations. Results show that these coefficient estimates all have good precision and goodness-of-fit. However, SUR provides more stable and efficient coefficient estimates, and is better if one is concerned about collinearity.

This equation system was used to project stand dynamics for light-thinned and heavy-thinned stands with an acceptable error. The implication of this result is that the status of crown size and stand density might affect the future growth and yield in response to different thinning intensities. The use of this equation system to project thinned stands can increase the efficiency and precision of optimizing the stand-level and forest-level management. This projection could be further improved if the basal area projection model were fitted with data from both unthinned and thinned stands, taking into account the thinning intensity, and if some better-fitted crown length model was used.

CONCLUSIONS

Schumacher's yield model could be used to develop a timber production function by the criteria of goodness-of-fit, minimum collinearity, and biological rationale. This timber production function can be used to examine the individual effect of the crown length and site index variables on stand growth and yield by the corresponding elasticity. The differentiation and integration method was used to develop a compatible growth equation. This method can mitigate serial correlation and collinearity. A new system of equations was developed to project stand dynamics. OLS, SUR, and 3SLS were used to estimate the parameters of this equation system. The SUR estimates are more efficient and stable and have a similar level of precision as the OLS and 3SLS estimates. This equation system can be used to project thinned stand volume per acre with an acceptable error.

Table 9. Summary statistics for the 171 sample plots in the Southeastern United States.

Variable	Minimum	Mean	Maximum
First measurement			
Age (year)	8.	15.5	25.
Volume (ft^3/acre)	257.1904	2343.9804	7950.6328
Basal area (ft^2/acre)	24.2876	114.7657	234.8782
Dominant height (ft)	14.40	41.68	74.03
Crown ratio	0.2537	0.4290	0.7150
Crown length (ft)	10.04	16.28	24.61
Trees per acre	299.	627.	1189.
Second measurement			
Age (year)	11.	18.5	28.
Volume (ft^3/acre)	590.1902	2962.7573	8596.3008
Basal area (ft^2/acre)	50.8801	131.7718	235.9535
Dominant height (ft)	21.75	47.71	79.75
Crown ratio	0.1967	0.3869	0.6635
Crown length (ft)	6.52	16.31	23.45
Trees per acre	309.	600.	1249.

Table 10. Estimates of parameters and the corresponding standard errors and t-values by OLS.

Parameter	Estimate	Standard Error	t-value
Yield Equation[a]			
a_1	-16.4678	0.6540	-25.18
a_2	0.0055	0.0005	12.00
a_3	-46.8649	3.4707	-13.50
a_4	0.0058	0.0015	3.81
Basal Area Equation[b]			
b_1	5.0769	0.0731	69.47
b_2	0.6678	0.0860	7.16
Dominant Height Equation[c]			
c_1	2.8657	0.3951	7.25
c_2	-6.2334	1.4845	-4.20
Crown Length Equation[d]			
d_1	0.8833	0.0914	9.66
d_2	0.0008	0.0003	2.55
d_3	-0.5725	0.0835	-6.85
d_4	-0.0354	0.0082	-4.29

a. $log(V/V_0) = a_1(1/A - 1/A_0) + a_2(B - B_0) + a_3(1/SI - 1/SI_0) + a_4(Cl - Cl_0)$

b. $B = \exp[(A_0/A)\log(B_0) + b_1(1 - A_0/A) + b_2(1 - Hd_0/Hd)]$

c. $Hd = Hd_0 \exp[c_1(e^{c_2/A} - e^{c_2/A_0})]$

d. $Cl = d_1 Hd/(1 + d_2 B) + d_3 Hd(1 - \exp[d_4(Hd - 4.5)])$

Table 11. Evaluation of the equation system with coefficient estimates by OLS.

Equation	FI[1]	MD[2]	SE[3]
Volume	0.9938	-21.807	97.326
Basal area	0.9606	-0.126	6.064
Height	0.9644	0.098	2.0348
Crown length	0.3623	0.095	2.536

1. $FI = 1 - \frac{\sum(\hat{Y} - Y)^2}{\sum(Y - \bar{Y})^2}$

2. $MD = \frac{1}{n}\sum(Y - \hat{Y})$

3. $SE = \sqrt{\frac{\sum(\hat{Y} - Y)^2}{(n-1)}}$

Table 12. Estimates of parameters and the corresponding standard errors and t-values by SUR and 3SLS.

Parameter	Estimate		Standard Error		t-value	
	SUR	3SLS	SUR	3SLS	SUR	3SLS
Yield Equation[a]						
a_1	-17.3589	-17.3660	0.6427	0.6437	-27.01	26.98
a_2	0.0048	0.0048	0.0005	0.0005	10.70	10.67
a_3	-49.6134	-49.5456	3.4121	3.4197	-14.54	-14.49
a_4	0.0063	0.0064	0.0015	0.0015	4.28	4.32
Basal Area Equation[b]						
b_1	5.0735	5.0756	0.0642	0.0638	79.06	79.52
b_2	0.6930	0.6909	0.0744	0.0740	9.31	9.34
Dominant Height Equation[c]						
c_1	2.5097	2.5408	0.1929	0.2075	13.01	12.24
c_2	-8.3679	-8.1368	1.4199	1.4260	-5.89	-5.71
Crown Length Equation[d]						
d_1	0.7821	0.7628	0.0603	0.0614	12.97	12.43
d_2	0.0013	0.0016	0.0005	0.0006	2.63	2.60
d_3	-0.5021	-0.4828	0.0595	0.0712	-8.44	-6.78
d_4	-0.0221	-0.0184	0.0081	0.0104	-2.71	-1.77

a. $log(V/V_0) = a_1(1/A - 1/A_0) + a_2(B - B_0) + a_3(1/SI - 1/SI_0) + a_4(Cl - Cl_0)$

b. $B = \exp[(A_0/A)\log(B_0) + b_1(1 - A_0/A) + b_2(1 - Hd_0/Hd)]$

c. $Hd = Hd_0 \exp[c_1(e^{c_2/A} - e^{c_2/A_0})]$

d. $Cl = d_1 Hd/(1 + d_2 B) + d_3 Hd(1 - \exp[d_4(Hd - 4.5)])$

Table 13. Evaluation of the equation system with coefficient estimates by SUR and 3SLS.

Equation	FI[1]		MD[2]		SE[3]	
	SUR	3SLS	SUR	3SLS	SUR	3SLS
Volume	0.9948	0.9938	-17.146	-17.398	97.309	97.3578
Basal area	0.9604	0.9605	-0.473	-0.484	6.078	6.0780
Height	0.9639	0.9640	-0.044	-0.040	2.049	2.0469
Crown length	0.3745	0.3756	0.231	0.241	2.547	2.558

1. $FI = 1 - \frac{\sum(\hat{Y} - Y)^2}{\sum(Y - \bar{Y})^2}$

2. $MD = \frac{1}{n}\sum(Y - \hat{Y})$

3. $SE = \sqrt{\frac{\sum(\hat{Y} - Y)^2}{(n-1)}}$

Table 14. Measure of collinearity for the predictor variables in the yield equation by OLS.

Variable	VIF[1]	CN[2]
Stand age	9.56	1.00
Basal area	9.31	1.32
Site index	1.23	1.86
Crown length	1.20	6.24

1. VIF is the inverse of unity minus the multiple correlation coefficient of one input variable that is regressed on the remaining input variables.

2. CN is the ratio of the corresponding eigenvalue to minimal eigenvalue of the input variable correlation matrix.

Table 15. Bias of projecting thinned stands by the coefficient estimates by OLS, SUR and 3SLS.

Equation	MD[1]			SE[2]		
	OLS	SUR	3SLS	OLS	SUR	3SLS
Light-thinned						
Volume	47.6030	36.9776	30.6049	174.427	175.460	174.5152
Heavy-thinned						
Volume	66.0125	55.4729	49.0913	171.171	169.471	167.9799

1. $MD = \frac{1}{n} \sum (Y - \hat{Y})$

2. $SE = \sqrt{\frac{\sum (\hat{Y} - Y)^2}{(n-1)}}$

Table 16. Estimates of the equation system without crown length by OLS, SUR and 3SLS.

Parameter	Estimate			t-value		
	OLS	SUR	3SLS	OLS	SUR	3SLS
Yield Equation[a]						
a_1	-16.4763	-17.7344	-17.7339	-24.24	-26.50	-26.50
a_2	0.0057	0.0048	0.0048	12.08	10.31	10.31
a_3	-50.3413	-53.4434	-53.4920	-14.47	-15.45	-15.47
Basal Area Equation[b]						
b_1	5.0769	4.9992	4.9988	69.47	69.26	69.26
b_2	0.6678	0.7695	0.7700	7.76	9.05	9.06
Dominant Height Equation[c]						
c_1	2.8657	2.9752	3.0117	7.25	6.62	6.38
c_2	-6.2334	-5.8547	-5.7398	-4.20	-3.99	-3.90

a. $log(V/V_0) = a_1(1/A - 1/A_0) + a_2(B - B_0) + a_3(1/SI - 1/SI_0)$

b. $B = \exp[(A_0/A)\log(B_0) + b_1(1 - A_0/A) + b_2(1 - Hd_0/Hd)]$

c. $Hd = Hd_0 \exp[c_1(e^{c_2/A} - e^{c_2/A_0})]$

Table 17. Bias of projecting thinned stands by the equation system without crown length by OLS, SUR and 3SLS.

Equation	MD[1]			SE[2]		
	OLS	SUR	3SLS	OLS	SUR	3SLS
Light-thinned						
Volume	38.6978	43.4022	43.5590	162.875	161.676	161.551
Heavy-thinned						
Volume	61.3094	64.7898	64.9137	165.151	165.165	165.136

1. $MD = \frac{1}{n} \sum (Y - \hat{Y})$

2. $SE = \sqrt{\frac{\sum (\hat{Y} - Y)^2}{(n-1)}}$

Chapter 5

TIMBER REMOVALS MODELS

INTRODUCTION

Timber removals include: (1) harvests of roundwood products such as sawlog, veneer logs, and pulpwood; (2) logging residues; and (3) other removals resulting from noncommercial thinning and changes in land use, such as cleaning for cropland, highways, or housing developments and withdrawals of commercial timberland for parks, wilderness and other nontimber uses (USDA Forest Service 1982). The forecasting of timber removals is necessary for updating future forest inventory.

Theoretically, most of timber removals are the equilibrium quantity resulting from the interaction of supply and demand in the stumpage market. The demand for timber in this market is primarily derived from the demand for wood products. Timber supply might be influenced by ownership, reservation price, inventory, legislation, and agency policy.

Many of the econometric models developed in forest economics have estimated demand and supply simultaneously in the lumber markets. Methodologically, supply and demand estimation for stumpage should be closely related to those models for lumber markets. Recently, Daniels and Hyde (1986), and Newman (1987) demonstrated solutions to the problem of supply and demand estimation in the stumpage market. Both studies estimated supply and demand for stumpage directly using simultaneous estimation of the supply and demand equations.

Although the simultaneous estimation approach is attractive for regional market analysis, several problems exist. First, demand determinants are likely to be different for different species. So the demand equation should be specified for different species. Second, the stumpage price is different for each species and also for ownership. Also, the harvest behavior might be different for various ownerships. So simultaneous equations for supply and demand of stumpage should be developed for each combination of species and ownership. Disaggregated economic data are needed to accommodate these problems and these do not always exist. When these simultaneous equations are used for forecasting future market equilibrium, projecting the exogenous variables is as important as the estimated model. Higher market models are needed to estimate some of exogenous variables. Also a regional projection should include net exports from that region. Econometric models with a national scope are required. Further, the quantity of timber sold in the market is usually less than the amount of timber removals. The non-commercial clearing portion usually needs additional projections. Therefore, the simultaneous estimation approach for forecasting the future timber removals is often sophisticated and time consuming to apply.

For these reasons, the simultaneous estimation was not performed in this study. Rather, a consumption function approach was used for forecasting removals. This pragmatic approach for forecasting timber removals as a function of market variables was a substitute for a simultaneous equation approach for the purpose of projecting future timber removals.

OBJECTIVES

The objectives of this study were two-fold. One was to develop a consumption function for softwood timber removals. The other was to demonstrate the use of this consumption function for forecasting softwood timber removals with TRIM, the Timber Resource Inventory Model (Tedder et al. 1987).

PROCEDURES

MODEL DEVELOPMENT

A theoretical model of stumpage supply and demand can be represented by simultaneous equations. For each combination of ownership and species, stumpage supply is assumed to be a function of the corresponding stumpage price and inventory. Stumpage demand is assumed to be a function of the stumpage price and the final goods price. The simultaneous equations are given as:

$$Q_{ij}^{s} = \alpha_0 + \alpha_1 P_{ij} + \alpha_2 I_{ij} \qquad [1]$$

$$Q_{ij}^{d} = \beta_0 + \beta_1 P_{ij} + \beta_2 F_{ij} \qquad [2]$$

$$Q_{ij}^{s} = Q_{ij}^{d} \qquad [3]$$

where Q_{ij}^{s} = the stumpage supplied from ownership i and species j

Q_{ij}^{d} = the stumpage demand for ownership i and species j

P_{ij} = the stumpage price for ownership i and species j

I_{ij} = the inventory available for ownership i and species j

F_{ij} = the final goods price for ownership i and species l

The corresponding reduced-form equations yield:

$$P_{ij} = \frac{\beta_0 - \alpha_0}{\alpha_1 - \beta_1} + \frac{\beta_2}{\alpha_1 - \beta_1} F_{ij} - \frac{\alpha_2}{\alpha_1 - \beta_1} I_{ij} \qquad [4]$$

$$Q_{ij} = \frac{\alpha_1 \beta_0 + \alpha_0 \beta_1}{\alpha_1 - \beta_1} + \frac{\beta_2 \alpha_1}{\alpha_1 - \beta_1} F_{ij} - \frac{\beta_1 \alpha_2}{\alpha_1 - \beta_1} I_{ij} \qquad [5]$$

where Q_{ij} is the quantity of stumpage in equilibrium. Equations [4] and [5] suggest that inventory available and final goods price determine the stumpage quantity and price in equilibrium. When these simultaneous equations are used to forecast timber removals, projecting the exogenous variables is as important as the estimated models. Also, disaggregated economic data are needed to accommodate these equations. It becomes sophisticated and time consuming to apply this direct estimation approach. For simplicity, a pragmatic consumption function approach was proposed in this study.

Several studies on modeling timber output from Virginia have been documented. Duerr (1960) proposed a hypothesis about landowner's harvesting behavior that timber output was related to the existing timber inventory and harvest decisions. Forest owners, based on the expectations of profitability, made the harvest decisions so as to maximize their utility. Based on this hypothesis, Hassler (1978) analyzed the timber output potential from eastern Virginia.

Straka (1981) developed a timber output model from Virginia's Coastal Plain. Results showed that timber removal per acre was a function of alternative rate of return, stumpage price, and timber volume per acre. Lawrence (1985) regressed harvest volume on current stumpage price, expected stumpage price, growth rate, landowner's discount rate, acres harvested, occupation of owner, age of owner, stand age, and total revenue. Results showed that current and past stumpage prices strongly influenced the harvest decision.

Although those studies provided a basis for prescribing regional timber removals models, the distinction of timber output from different ownership and species was ignored in most past studies. Stumpage price and harvest behavior should vary with species and ownership. Also, timber removals include commercial harvest and non-commercial clearings. Removals from commercial harvest might be affected by inventory, timberland area, and stumpage price, while non-commercial clearing could be affected by some non-economic factors. Usually, it is difficult to specify variables for the non-commercial removals portion. Also, the portion of non-commercial clearing is relatively small, compared to the commercial removals. So, the factors that affect non-commercial clearing are included in the commercial removal determinants. That is, total removals are assumed a function of commercial removal determinants. The proposed consumption model for timber removals is:

$$TR_{ij} = f[P_{ij}(+), I_{ij}(+), A_{ij}(+)]$$

TR_{ij} is the timber removals, in million cubic feet, from ownership i and species j. The amount of timber removals includes commercial harvest and non-commercial clearings. P_{ij} is the weighted timber price in 1967 dollars per thousand board feet for ownership i and species j. The selection of this weighted timber price considered the fact that the primary products of stumpage include saw log, veneer log, pulpwood, and chip. So the portion of each primary product is used to weight the corresponding stumpage price. I_{ij} is the inventory available, in million cubic feet, from ownership i and species j; and A_{ij} is the timberland area, in thousand acres, for ownership i and species j. The ownership categories include National Forest (NF), Other Public (OP), Forest Industry (FI), and Other Private (FP), while species include softwood only.

The greater the stumpage price, the larger the timber removals. The expected sign for stumpage price is positive. However, this expected sign might be affected by the complementary relationship between sawtimber and pulpwood. For example, if sawtimber stumpage price displays a positive effect on supply, pulpwood stumpage price might have a negative effect. Also, switching of production from pulpwood to sawtimber is relatively easy when the size of timber is large enough for both uses. The price coefficient is assumed to be positive, since sawtimber is the major use of stumpage in Virginia and the complementary effect might be small.

The expected sign for inventory is positive. For private forest owners, the greater the inventory available, the more the potential timber supply and the more likely the forest owners want to sell timber. For public landowners, the amount of timber removals might be largely affected by non-economic factors, e.g. policy decisions for wildlife protection. So, the sign is uncertain for the public sector.

The expected sign for timberland area is uncertain. Usually, the larger the timberland area, the more inventory is available. However, the increases of net growth due to high management intensity might offset the decrease of timberland area to increase the inventory, which in turn might increase timber removals. So, the decrease of timberland area does not necessarily imply the decrease of inventory.

DATA

The forest surveys in Virginia conducted by USDA Forest Service in 1952, 1962, 1970, 1976, and 1984 provide information about changes and trends of timber removals and other forest resources over the past decades. The inventories are samples designed to provide reliable statistics on forest resources in Virginia (see Brown 1986 for detailed descriptions). Table 18 provides this information. These resource data help provide a basis for understanding the development and use of the resources.

Timber Removals

The estimates of timber removals include the merchantable volume of trees removed from the inventory by harvesting, cultural operations such as stand improvement, land clearing, or changes in land use. The data for timber removals in million cubic feet were compiled for softwood and hardwood species and for National Forest, Other Public, Forest Industry, Farmer, Private Corporate, and Private Individual ownerships by USDA Forest Service (1987a) in selected years from 1952-1984. The ownership categories from Farmer, Private Corporate, and Private Individual were aggregated to form Other Private ownership, since the private individual data were not available in 1952, 1962, and 1970. The time series data of softwood timber removals are shown in Table 18. The timber removals from National Forest and Other Public were only 13 percent of the total removals from Virginia in the past decades.

Stumpage Price

There is no statewide stumpage price series in Virginia that includes stumpage sold from each ownership and species group covered over the whole study period. The analysis used a weighted stumpage price of southern pine sawtimber and pulpwood in Louisiana for softwood timber price sold from the private sector (see USDA Forest Service 1987b for stumpage price data source) as a surrogate of softwood timber price. The selection of proportion to weight the corresponding stumpage price depends on the production of each primary product in Virginia. Parts of this information were obtained from Hotvedt (1975) and Bechtold et al. (1987). The stumpage price of southern pine sold from National Forest was used for softwood timber price sold from the public sector (USDA Forest Service 1987b). These annual weighted timber prices were averaged as periodic data to accommodate the periodic timber removals data (Table 18).

Inventory

Together with timber removals data, inventory is one of the important measures of resource changes and can be projected using a forest inventory projection model. The trend-level estimates of growing stock were based on periodic remeasurement of permanent sample plots at 5- to 10-year intervals. The data for inventory in million cubic feet were compiled for softwood and hardwood species and for National Forest, Other Public, Forest Industry, Farmer, Private Corporate, and Private Individual ownerships by USDA Forest Service (1987a) in selected years from 1952-1984. The ownership categories from Farmer, Private Corporate, and Private Individual were aggregated to form Other Private ownership. The quantity of periodic inventory is the growing-stock volume in growing-stock trees 5.0 inches d.b.h. and larger, from a 1-foot stump to a minimum 4.0-inch top diameter, outside bark, on the central stem measured at the end of each survey period. The time series data for softwood inventory in Virginia are shown in Table 18.

Timberland

The area of timberland includes the land at least 16.7 percent stocked by forest trees of any size, or formerly having had such tree cover, capable of producing 20 cubic feet of industrial wood per acre per year and not withdrawn from timber utilization by legislative action. The data for timberland area in thousand acres were compiled for each ownership and management type in Virginia by USDA Forest Service (1987a) in selected years from 1952-1984. The timberland area data for each forest management type were aggregated into softwood and hardwood species to accommodate timber removals data. The time series data for softwood timberland area are shown in Table 18.

RESULTS

MODEL ESTIMATION

The Box-Cox transformation is used to examine the possible functional form for the timber consumption models (Judge et al. 1985). By the Box-Cox transformation, three types of data-transformed models are:

$$\frac{TR_{ij}^r - 1}{r} = \alpha_0 + \alpha_1 \frac{P_{ij}^r - 1}{r} + \alpha_2 \frac{I_{ij}^r - 1}{r} + \alpha_3 \frac{A_{ij}^r - 1}{r}$$

$$\frac{TR_{ij}^r - 1}{r} = \beta_0 + \beta_1 P_{ij} + \beta_2 I_{ij} + \beta_3 A_{ij}$$

$$TR_{ij} = \gamma_0 + \gamma_1 \frac{P_{ij}^r - 1}{r} + \gamma_2 \frac{I_{ij}^r - 1}{r} + \gamma_3 \frac{A_{ij}^r - 1}{r}$$

where r = the parameter used to determine the functional form
$\alpha_0,\ \alpha_1,\ \alpha_2,\ \alpha_3,\ \beta_0,\ \beta_1,\ \beta_2,\ \beta_3,\ \gamma_0,\ \gamma_1, \gamma_2,\ \gamma_3$ = the coefficients to be estimated

Those transformations can be used to stabilize the variance of time series data. The boundary cases correspond to a logarithmic transformation if $r = 0$ and a simple mean reduction if $r = 1$. The choice of r depends on the data using the concentrated likelihood function. That is,

$$L(r) = -\frac{n}{2}\log(RSS(r)) + (r-1)\sum_{t=1}^{n}\log(TR_t)$$

where n is the number of observations; and $RSS(r)$ is the residual sum of squares after fitting the regression model with r at the chosen value. The basic idea of choosing optimal r is that if the variance estimated is smaller for some r, the corresponding model is better for the data.

For each type of data-transformed models, the corresponding maximum likelihood estimator $\hat{r}$ can be found by (i) choosing a reasonable range of values for r; (ii) using least squares to calculate $RSS(r)$ for each value of r; and (iii) choosing the r for which $L(r)$ is maximized. Also, the stepwise regression procedure was used to reduce the number of predictor variables using the t-value criterion. If the t-value for some predictor variable is not significant at the 7.5 percent level, this predictor variable is dropped from the equation. Finally, comparison of standard errors for each resulting type of data-transformed models was used to select the best functional form for the consumption model.

The concentrated likelihood function, the t-value and the standard error suggest that the following functional forms, variables, and coefficients provide the best estimate.

$$\log(TR_{NF,S}) = 225.9902 - 71.2577\log(I_{NF,S}) - 30.2782\log(A_{NF,S}) + 84.9684\log(P_{public,S}) \quad SE = 0.0078 \quad FI = 0.99 \quad DW = 3.181 \tag{6}$$

$$TR_{OP,S} = 31.0013 - 0.0465 I_{OP,S} - 0.1228 A_{OP,S} + 0.2123 P_{public,S} \quad SE = 0.0394 \quad R^2 = 0.99 \quad DW = 1.974 \tag{7}$$

$$\log(TR_{FI,S}) = -3.9040 + 0.8593\log(I_{FI,S}) - 0.4640\log(A_{FI,S}) + 1.2929\log(P_{private,S}) \quad SE = 0.0464 \quad FI = 0.99 \quad DW = 2.816 \tag{8}$$

$$TR_{FP,S} = -37.5788 + 0.0334 A_{FP,S} + 1.5295 P_{private,S} \quad SE = 1.4062 \quad R^2 = 0.99 \quad DW = 3.396 \tag{9}$$

Subscripts S represents species for softwood. Subscripts NF, OP, FI and FP represent ownership for National Forest, Other Public, Forest Industry, and Other Private, respectively. Subscripts *public* and *private* represent the public sector and the private sector. The relatively small standard error and high R^2 or fit index (FI) show that those fitted removals models have a high goodness-of-fit performance. The Durbin-Watson statistics indicate that no serial correlation can be detected.

These timber removals models show that some of the coefficient estimates carry the wrong sign. For instance, the sign for the inventory variable in equations [6] and [7] is negative. This may result from collinearity among predictor variables, especially the existence of the timberland area variable. Another possible reason for this negative sign is that the timber removals from public ownerships were not directly affected by the inventory volume. The negative sign indicates that the larger the inventory, the smaller the timber removals. There is a difference of opinion among forest economics about whether the inventory sign should be positive or negative. However, this study specified positive so this contradiction in model specification jeopardizes equations [6] and [7] as predictors of future timber removals, if inventory is hypothesized to be a major supply shifter. Equations [6] and [7] also suggest that the timber removals from the public sector might be affected by the stumpage price. This result contradicts several early studies on timber harvest behavior on the public sector (e.g. Buongiorno et al. 1985). One possible reason for this contradiction is that the averaged stumpage price used in this study lost lots of degrees of freedom. So those two models can not be used to describe the actual harvest behavior.

Equation [8] suggests that the softwood timber removals from Forest Industry can be significantly affected by inventory, timberland area, softwood timber price. The sign of the timberland area variable is negative and might contradict the harvest behavior. However, this wrong sign might not affect the forecasting of timber removals if one assumes that the timberland area will not fluctuate too much in the near future. Equation [9] says that the softwood timber removals from other private can be predicted by timberland area and softwood timber price. The signs in this equation are consistent with harvest behavior. The inventory variable is not significant in this model.

Plots of observed versus estimated timber removals data over the sample period were used to show the goodness-of-fit of those timber removals models. Figure 1 shows that the timber removals model for National Forest/softwood is very precise for estimating periodic timber removals in the sample period. Ninety nine percent of variation in timber removals can be accounted for by the predictor variables. Figure 2 shows that the timber removals model for Other

Public/softwood has strong goodness-of-fit performance. This model accounts for 99 percent of the variation in timber removals. Figure 3 shows that the timber removals model for Forest Industry/softwood also have strong goodness-of-fit performance. This model also accounts for 99 percent of the variation in timber removals. Figure 4 shows that the timber removals model for Other Private/softwood has a relatively larger difference between observed and estimated data. But the mean difference and the standard error are small and acceptable. This model also accounts for 99 percent of the variation in timber removals.

In summary, all the softwood timber removals models have strong goodness-of-fit performance. However, the wrong sign jeopardizes two of them for the prediction of future timber removals. The existing forecasts of timber removals based on Forest Service projection are suggested for National Forest and Other Public to replace these two model estimates. Equations [8] and [9] may have highly accurate forecasts of future timber removals from Forest Industry and Other Private.

MODEL USE

Timber removals models [8] and [9] can be used with TRIM to estimate future timber removals from Forest Industry and Other Private. The output from TRIM provides inventory and timberland area information for each ownership. This information can be used to estimate the exogenous variables in the timber removals models. The only predictor variable that can not be estimated from TRIM is the stumpage price. Theoretically, the stumpage price is endogenously determined by the market forces. The best way to estimate stumpage price is to use simultaneous supply and demand equations for solving the equilibrium point. However, an alternative exists. One can develop a price expectation model for the softwood weighted timber price. Then an extrapolation is made to project this future stumpage price.

The way of using timber removals models with TRIM is given as follows. At the initial period, TRIM is run and gives current inventory and timberland area information for each ownership and species, given some initial guess for the current timber removals. Together with the projected stumpage price, the system of timber removals equations uses the inventory and timberland area information from TRIM to predict current timber removals. If the predicted timber removals equal the guessed timber removals, then the procedure proceeds to the next period. Otherwise, one needs to replace the guessed timber removals with the predicted one and run TRIM again until the criterion is reached. Since TRIM accepts only periodic timber removals, the predicted removals from the timber removals model should multiply the length of period or age class in the yield table. This iteration procedure is made between TRIM and these timber removals models to project inventory, timberland area, and timber removals for any planning horizon. Since this iteration procedure requires a positive sign for the inventory variable in the removals model, equations [6] and [7] can not work with TRIM using this procedure to project future timber removals.

SUMMARY AND CONCLUSIONS

Most of timber removals represent the quantity of timber supply in the stumpage market. The estimates of timber removals thus can be done using simultaneous timber supply and demand equations. For simplicity, a pragmatic consumption function approach was adopted. The Box-Cox transformation, the stepwise regression procedure, and the standard error criterion were used to select the functional form of timber removals models for each ownership/species category. All these timber removals models have strong goodness-of-fit performance for the historic data. However, the wrong sign makes two of them questionable to work with TRIM for projecting future timber removals. The existing forecasts of timber removals are suggested for National Forest and Other Public. The softwood timber removals models for Forest Industry and Other Private may provide a highly accurate forecast of future timber removals. These two models can be used with TRIM to project future forest inventory and timber removals.

Table 18. Softwood timber removals, inventory, stumpage price, and timberland area in Virginia, by ownership, 1952-1984.

Ownership	1952	1962	1970	1976	1984
National Forest					
Timber removals (10^6ft^3)	1	1	1	5	1
Inventory (10^6ft^3)	223	213	229	291	309
Timberland area (10^3acres)	141	121	122	151	175
Stumpage price (dollar/MBF)	38.03	34.66	36.93	49.65	54.00
Other Public					
Timber removals (10^6ft^3)	9	7	8	10	6
Inventory (10^6ft^3)	215	205	233	275	327
Timberland area (10^3acres)	163	178	163	153	173
Stumpage price (dollar/MBF)	38.03	34.66	36.93	49.65	54.00
Forest Industry					
Timber removals (10^6ft^3)	33	27	29	46	60
Inventory (10^6ft^3)	778	744	840	877	1,104
Timberland area (10^3acres)	483	644	805	918	1,029
Stumpage price (dollar/MBF)	33.72	32.91	34.85	50.70	55.60
Other Private					
Timber removals (10^6ft^3)	172	143	128	144	139
Inventory (10^6ft^3)	3,911	3,743	3,782	4,069	4,158
Timberland area (10^3acres)	4,743	3,832	3,4075	3,097	2,742
Stumpage price (dollar/MBF)	33.72	32.91	34.85	50.70	55.60

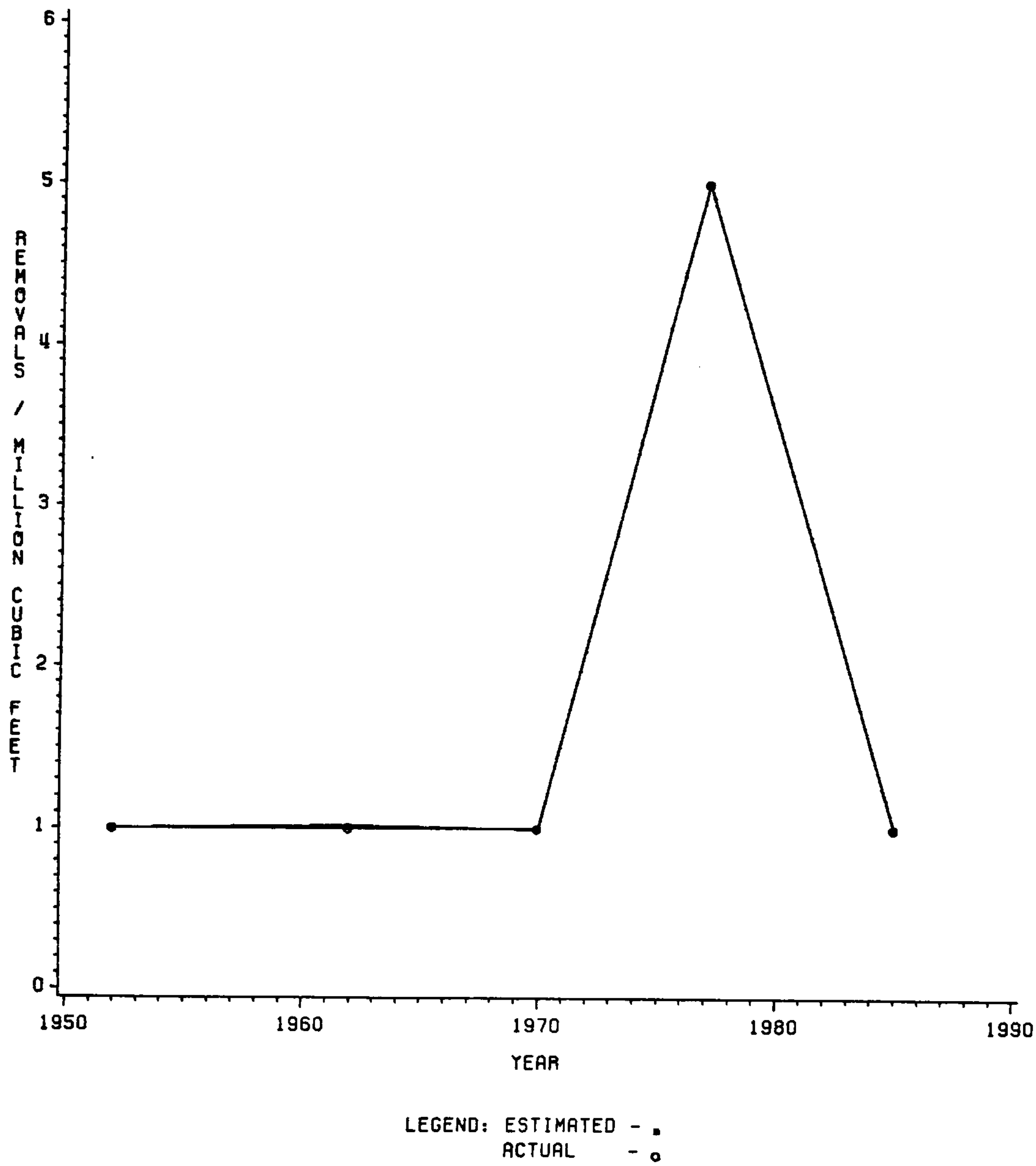

Figure 1. Plots of actual versus estimated values for timber removals from National Forest over time period.

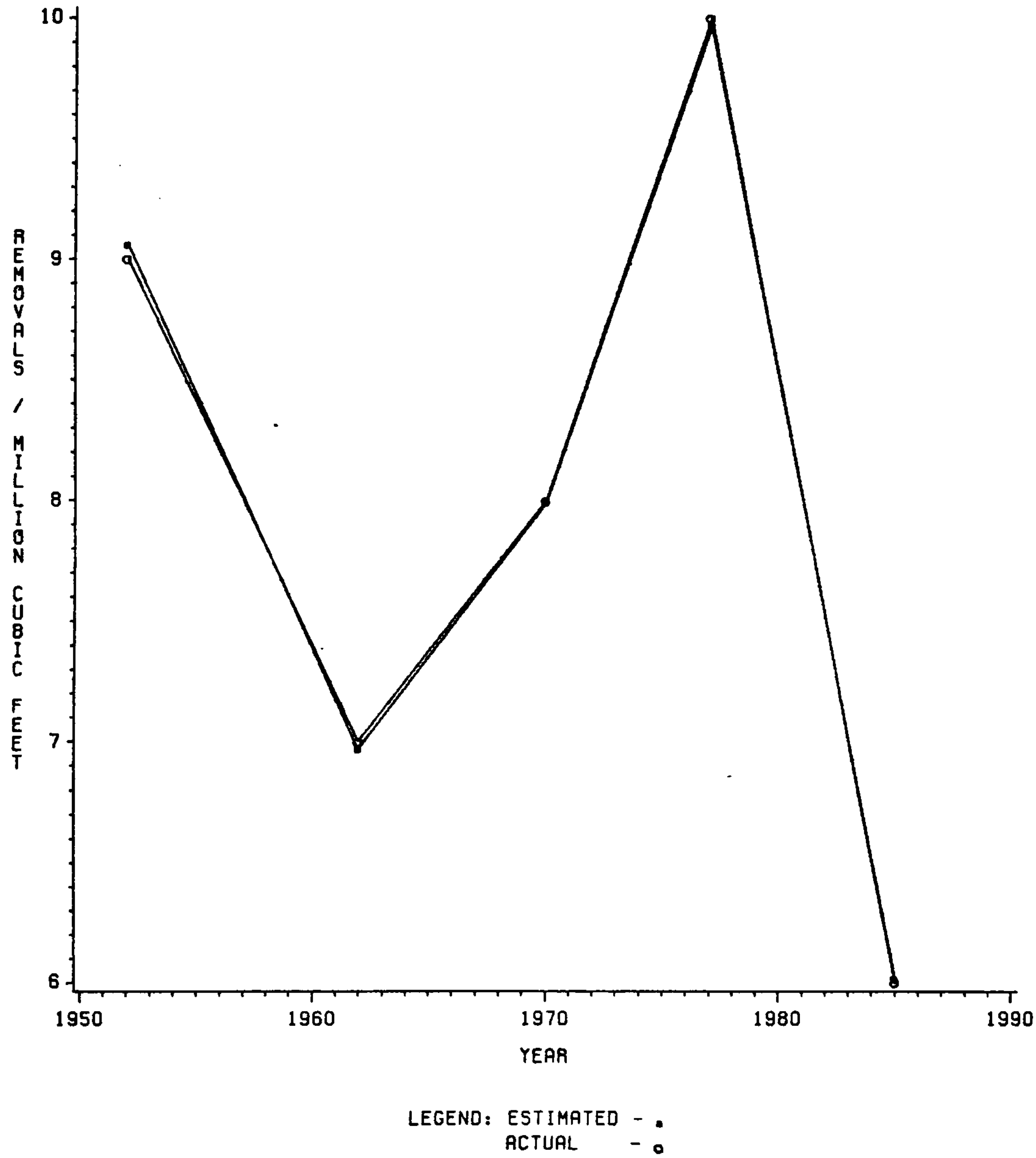

Figure 2. Plots of actual versus estimated values for timber removals from Other Public over time period.

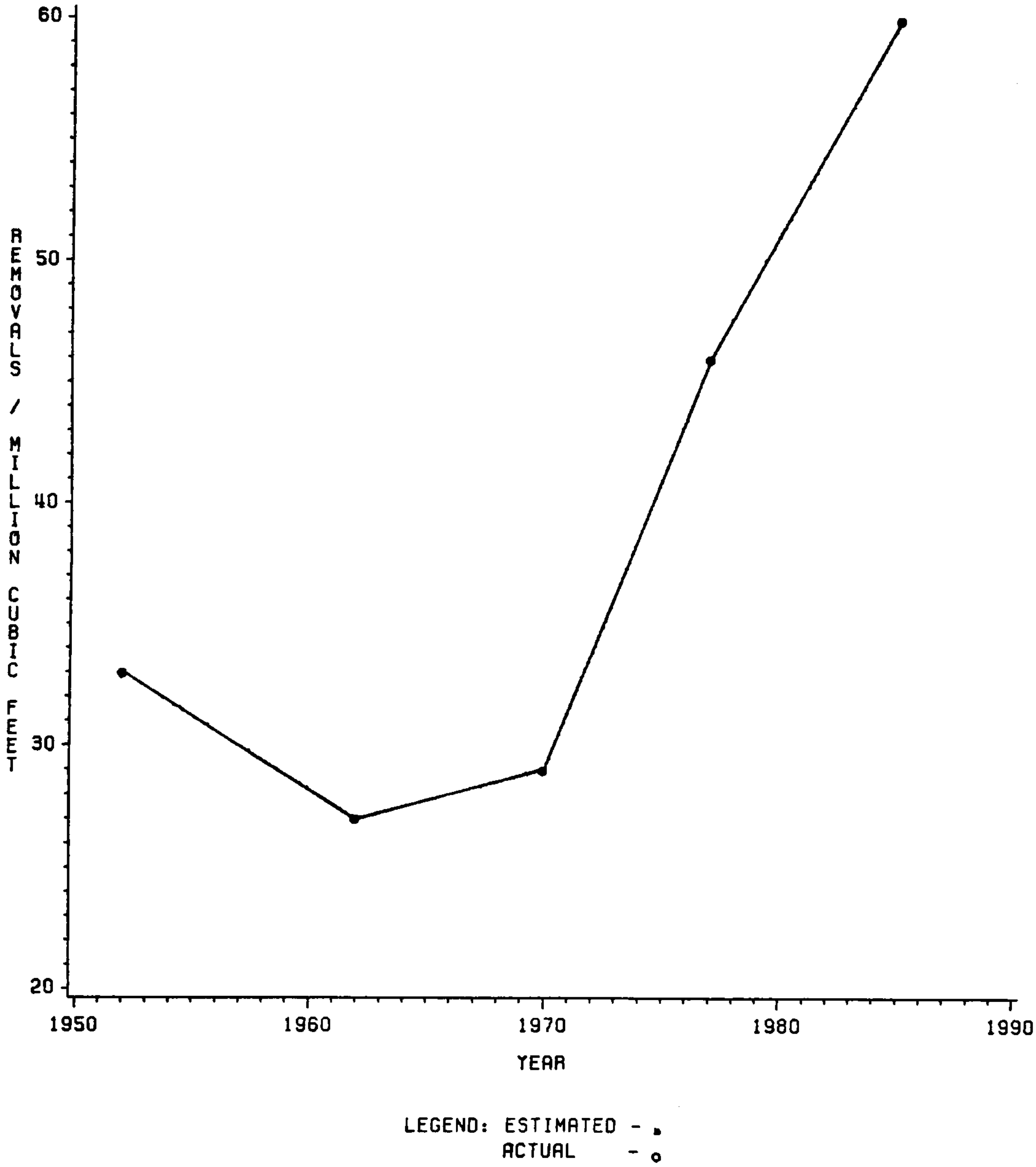

Figure 3. Plots of actual versus estimated values for timber removals from Forest Industry over time period.

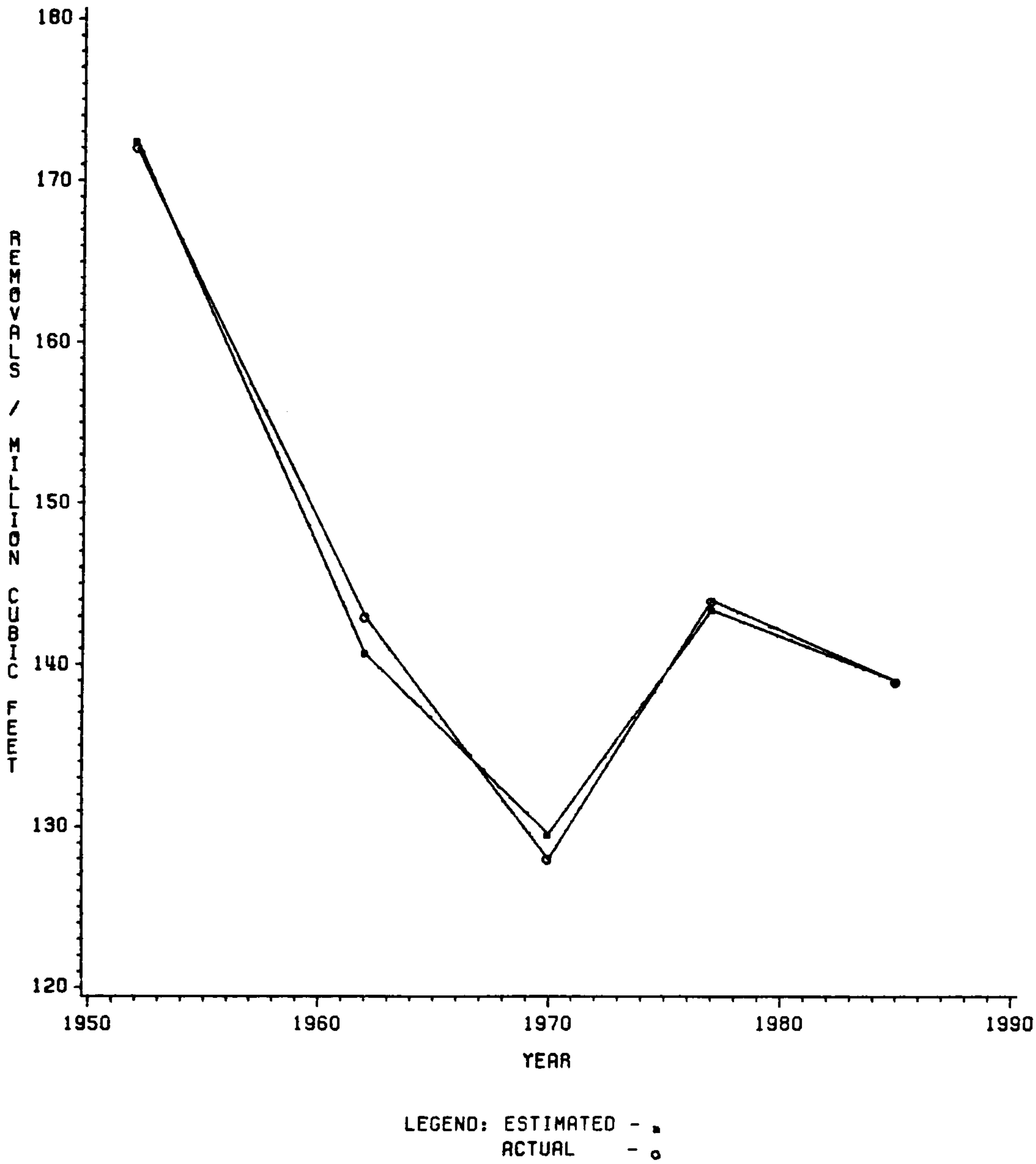

Figure 4. Plots of actual versus estimated values for timber removals from Other Private over time period.

Chapter 6

A DECISIONMAKING FRAMEWORK FOR ASSESSING ATMOSPHERIC DEPOSITION IMPACTS

INTRODUCTION

The prospects of both increasing atmospheric deposition and decreasing forest productivity have concerned decisionmakers in forestry and environmental policy. Decreasing forest productivity could reduce physical inventory and timber supply. The timber inventory is not only important to the forest industry which harvests the timber but it is also important to the large population which uses the forests' other multiple-use products. Tree growth declines and visible foliage damage in east coast forests are very often attributed to atmospheric pollution. Although the precise biological impacts of pollution on forests are still undetermined, a decisionmaking framework should be developed concurrently so the biological information can be used as soon as it is available.

A decisionmaking framework should provide the information about the changes of inventory in response to different pollution levels. This decisionmaking framework requires at least three interrelated segments. The first is a forest inventory projection model. This model should use yield and management information, initial inventory data, and timber harvest information to project future forest inventory. The second is a timber production function which provides a separate effect of some biological variable on stand growth and yield. This biological variable should reflect the forest's likely state in response to different pollution levels. The third is an econometric model that can forecast the future timber removals. Once this decisionmaking framework is developed, decisionmakers can use it to quantify possible impacts of atmospheric deposition on forest inventory. This information is very important to cost-benefit analysis for regulating the use of fossil-fuel and controlling air pollutant standards in industries.

OBJECTIVES

The objectives of this study were two-fold. First, to integrate a forest inventory projection model, a timber production function, and an econometric model to form a decisionmaking framework for simulating future forest inventory. Second, to apply this decisionmaking framework to the softwood inventory data in Virginia to demonstrate the possible impacts of atmospheric deposition on inventory.

PROCEDURES

The first step was to show the use of a forest inventory projection model for examining environmental impacts on inventory. The second step was to show how a timber production function can be used to estimate the influence of some biological variable on stand growth and yield. This biological variable should reflect atmospheric deposition impacts on stand growth and yield. The third step was to show the interactions between an econometric model and this inventory projection model in determining future inventory levels. The fourth step was to link this forest inventory projection model with the timber production function and the econometric model. This linkage forms a decisionmaking framework that can be used for assessing atmospheric deposition impacts on forest inventory. The fifth step was to demonstrate the use of this decisionmaking framework for examining the impacts of atmospheric deposition on the softwood forest inventory in Virginia.

FOREST INVENTORY PROJECTION MODEL

Regional inventory projection techniques have evolved from simple formulas through more elaborate diameter class models to highly disaggregated age class-ownership models. This study uses one newly developed forest inventory projection system, the Timber Resource Inventory Model (TRIM) (Tedder et al. 1987), to project forest inventory in Virginia. TRIM is used because (i) it is designed to use USDA Forest Service Forest Inventory and Analysis data (the only data available); (ii) it is already developed and documented; and (iii) it requires an exogenous forecast of timber removals which can reflect supply and demand interactions as inventory levels shift.

TRIM is a yield-table projection system designed and developed for simulating forest inventory changes over time. The number of timberland acres and volume per acre is entered by age class, stocking level, and management intensity. Yield and management information is specified, including yield, thinning, and mortality tables by age class and management intensity, specifications for shifting acres among management intensities, treatment options and other options, revenue and cost data for economic reports, and volume unit conversion factors. Also, time and harvest information is specified.

The principal algorithms in TRIM are those which simulate inventory projection, harvest, and regeneration. There are two options for projecting inventory. One is the yield table method. The other is the approach-to-normality method. The yield table method is used here because the approach-to-normality method was judged to add nothing substantial to the analysis. Also insufficient knowledge exists to quantify variables needed in the approach-to-normality equation (see Chapter 3).

The harvest volume in each period is determined exogenously and is allocated to each age class at the beginning of each period. Preferred harvest proportions by age class or an oldest first priority may be specified. The harvest volume is allocated to the age classes in a descending order if oldest first priority is used. If a preferred harvest proportion is assigned and harvest request is not exhausted, the program reverts to an oldest first priority. Oldest first priority is used for this analysis.

Once the harvest has been allocated and removed, regeneration is simulated for the acres just cutover and those acres that have been shifted into the timberland base from the unstocked category. These stands then grow again to the end of the period and the inventory reported is the sum of volume from each age class.

The TRIM algorithms do not contain any biological models for simulating stand growth and yield in response to atmospheric deposition impacts. Since atmospheric deposition impacts on forest inventory are primarily through the biological growth of stands, the input variables related to stand growth and mortality need to be modified. At least four groups of candidate variables should be considered according to the types of forest injury. These include variables related to growth, mortality, the management decisions associated with growth and mortality, and the harvest decisions.

By sensitivity analysis and an *a priori* analysis, it can be shown that growth and harvest decision variables have the greatest affect on the projected inventory. So modification of growth and harvest decision variables is the most promising for impact projection. Modification of the growth variables requires choosing either the yield table or approach-to-normality method. The yield table method has several advantages. It is the simplest to understand, the simplest to modify, and implicitly assumes a constant stocking level throughout stand life. Only the yield tables should be changed to reflect atmospheric deposition impacts. If some exogenous biological information is available, we can simply modify the yield tables for simulating impacts. A timber production function approach was used to extract this biological information.

Ending inventory is obviously affected by the harvest request because this is a direct subtraction from the inventory. However, the harvest request is unlikely to be directly impacted by atmospheric deposition. The impact will most likely be seen if atmospheric deposition causes a major supply shift. A timber consumption function approach was used to estimate the harvest information.

APPLICABILITY OF TIMBER PRODUCTION FUNCTION

A timber production function that includes some biological and/or environmental factors can be used to assess environmental impacts on timber production. Schumacher's yield model was adopted to describe timber production process. The selection of functional form and predictor variables depends on goodness-of-fit, biological rationale, and minimum collinearity. Once a timber production function is developed, the corresponding input-output and input-input relationships can be used to infer the individual influence of the biological variable on stand growth and yield.

The proposed timber production function for loblolly pine plantations in the Southeastern region is:

$$\log(V) = a_0 + a_1 \frac{1}{A} + a_2 B + a_3 \frac{1}{SI} + a_4 Cl \qquad [1]$$

where V = the volume per acre ($ft^3/acre$)
A = the stand age
B = the basal area per acre ($ft^2/acre$)
SI = the site index based on age 25
Cl = the crown length in feet
$a_0, a_1, a_2, a_3, a_4,$ = coefficient estimates

Recent studies on stand characteristics suggested that crown length can reflect certain environmental impacts on tree growth. Since crown length represents some characteristics of crown size, which is directly related to photosynthetic potential of trees, the anabolic growth rate might be larger for a longer crown length. Reduction in photosynthesis by atmospheric deposition can be assumed partly due to the reduction of crown length. Thus inclusion of the crown length variable in this timber production function allows simulating the impacts of atmospheric deposition on stand growth and yield.

By statistical analysis, equation [1] was fitted with remeasurement data using differentiated and integrated model forms (see Chapter 4). Also, a system of predictor equations was added to this yield equation and seemingly unrelated regressions (SUR) were used to mitigate against the serial correlation and collinearity problems. Table 19 shows the result of fitting for SUR coefficient estimates, and the corresponding standard error, t-value, variance inflation factor (VIF), and condition number (CN). All the coefficient estimates are significantly different from zero at the 5 percent level. This suggests that all the predictor variables could have significant contribution to the variations of the output variable. The signs for all predictor variables are consistent with biological knowledge. The VIF's for the site index and crown length variables indicate that the variance of the corresponding coefficient estimates is not affected by collinearity. For stand age and basal area variables, the relatively large VIF's indicate that the variance of these coefficient estimates could be affected by collinearity. If interest centers on site index or crown length (the relatively unaffected parameter estimates), clearly no collinearity problem exists. The CN's signal that the coefficient estimates are not sensitive to the minor perturbation in the input data.

The fit index, mean difference, and standard deviation of the differences between estimated and observed data for this equation are 0.995, -17.146, and 97.309, respectively. The high fit index implies that the predictor variables account for 99.5 percent of the variation in the dependent variable. The mean difference indicates that predicted volumes are slightly over-estimated. This over-estimation might be inconsistent with the assumption of OLS but not important in overall prediction. The relatively small standard error, compared to the mean value statistics, 2653.4 ft^3/acre, implies that this equation may have good extrapolation properties.

The partial elasticity of timber output with respect to crown length provides a measure of the individual biological contribution to the timber production. The value of this elasticity tells the percentage change in volume for a one percent change in crown length. The formula for this elasticity is:

$$E_{(V,Cl)} = \left(\frac{\partial V}{\partial Cl}\right)\left(\frac{Cl}{V}\right) = a_4 Cl \qquad [2]$$

Rearranging this formula gives:

$$\partial V = a_4 V \, \partial Cl \qquad [3]$$

Equation [3] says that the changes in volume per acre due to certain environmental impacts can be quantitatively determined by the current state of stand volume and the changes of crown length due to these environmental impacts. Given that a yield table is available for a certain stand and a precise environmental impact on crown length is known, one can use equation [3] to assess the changes in this yield table due to this certain environmental impact for loblolly pine plantations. This information might be applied to other softwood species to approximate atmospheric deposition impacts on them.

TIMBER REMOVALS MODEL

The forecasts of timber removals are a necessary input for updating future forest inventory. Most of timber removals are the equilibrium quantity resulting from the interaction of supply and demand in the stumpage market. So timber removals can be estimated by simultaneous equations of supply and demand. The simultaneous estimation is sophisticated and time consuming because of data unavailability and additional projections needed for exogenous variables. Therefore, a consumption function approach was used here to forecast timber removals.

The proposed timber removals model assumes the timber removals as a function of inventory, stumpage price, and timberland area. Since stumpage price and harvest behavior might be different for different species and ownership, different timber removals models should be specified for each combination of ownership and species. The ownership categories include National Forest (NF), Other Public (OP), Forest Industry (FI), and Other Private (FP). The only species category used is softwood. Results show that the timber removals models for Forest Industry and Other Private can be used with TRIM to simulate the interactions between timber removals and inventory levels (see Chapter 5). The existing forecasts of timber removals were a supplement to the model estimates, especially for those from Nation Forest and Other Public (Table 20). The developed timber removals models (TRM) for Forest Industry and Other Private are:

$$\log(TR_{FI}) = -3.9040 + 0.8593\log(I_{FI}) - 0.4640\log(A_{FI}) + 1.2929\log(P) \qquad [4]$$
$$SE = 0.0464 \quad FI = 0.99 \quad DW = 2.816$$

$$TR_{FP} = -37.5788 + 0.0334A_{FP} + 1.5295P \qquad SE = 1.4062 \quad R^2 = 0.99 \quad DW = 3.396 \qquad [5]$$

TR_i is the timber removals in million cubic feet from ownership i. The timber removals include commercial harvest and non-commercial clearing in Virginia. I_i is the inventory available in Virginia, in million cubic feet, for ownership i. A_i is the timberland area in thousand acres for ownership i. P is the averaged timber price in 1967 dollars per thousand board feet for the private sector. Since there is no statewide stumpage price series in Virginia that includes stumpage sold from each ownership and species covered the whole study period, the weighted stumpage prices of sawtimber and pulpwood in Louisiana were averaged as periodic timber price for the private sector (USDA Forest Service 1987b). The proportion of each forest primary product in Virginia was used to weight the corresponding stumpage price. Subscripts FI and FP represent ownerships for Forest Industry and Other Private.

The relatively small standard error and high R^2 or fit index (FI) show that these two fitted timber removals models have a strong goodness-of-fit performance. The Durbin-Watson statistics indicate that no serial correlation can be detected in these models.

These timber removals models were used with TRIM to project future inventory and removals. The output from TRIM provides inventory and timberland area information for each model. Only the stumpage price variable in these two models can not be estimated by TRIM. A price expectation model was developed to extrapolate the future weighted timber price.

The developed timber price expectation model for the private sector is:

$$P_t = 7.0638 + 0.8335P_{t-2} + 0.9920(P_{t-1} - P_{t-2}) \qquad SE = 6.5849 \quad R^2 = 0.73 \quad DW = 1.917 \qquad [6]$$

where P_t is the annual timber price at year t. The use of this price expectation model needs price information in the previous two periods. The price series generated by the price expectation model converges to some value. This convergence depends on the coefficient and the sign of the difference term. The positive sign suggests that the generated price series will be in an ascending order. The larger the value for this coefficient, the slower the convergence.

INTEGRATION OF TRIM|TPF|TRM

Integration of the Timber Resource Inventory Model (TRIM), the timber production function (TPF), and the timber removals model (TRM) forms a decisionmaking framework for assessing environmental impacts on softwood inventory in Virginia. The linkage of TPF with TRIM is straightforward. It can be done simply by modifying the yield tables in TRIM given that the changes in crown length due to some atmospheric deposition impacts are known. The development of TPF is for loblolly pine plantations. It is assumed that the information from equation [3] can be applied to other management types and softwood species. Combining equation [3] with the yield tables in TRIM, we can modify the volume per acre in the yield tables, assuming several scenarios of crown length change.

The linkage of TRIM with TRM needs some start-up procedure. This start-up procedure is necessary because the timber removals model needs a current inventory level, timberland area, and stumpage price to estimate the current timber removals. TRIM needs current timber removals to provide inventory and timberland area information, but the removals model also needs current inventory to estimate current removals. Thus, a simultaneous solution is needed. One of these two models should first provide an initial estimation for the other and then iterations can be made to modify this initial estimation. Tedder (1983) pointed out this problem when he tried to integrate TRIM with TAMM. In most cases, it is easier to estimate removals and run the TRIM programs. So the start-up procedure to link TRIM with TRM is:

Step 1. Estimate an initial value of timber removals using the actual removals in the previous period.

Step 2. Extrapolate the averaged timber prices from equation [6].

Step 3. Run TRIM using the yield table method with given timber removals.

Step 4. Project timber removals using TRM with information from Steps 2 and 3.

Step 5. Test if the difference between projected and estimated removals is within tolerance level. If not, substitute the estimated value with the projected value and go back to Step 3.

During each period, the estimate for timberland area and averaged timber price is not affected by this start-up procedure. Only the removals value is adjusted up or down according to the corresponding timber removals model. Due to the variants of functional form for the timber removals model, this start-up procedure does not guarantee the convergence of the estimated and projected removals. This convergence depends on the sign of the inventory variable in the timber removals model. Removals models that include the inventory variable with a negative sign can not work with this start-up procedure, since it is not possible to converge and the linkage with TRIM is impossible. Also, the removals model including no inventory variable needs only one loop of this start-up procedure to generate timberland area information, because timberland area is independent of other factors in TRIM. When the criterion in Step 5 is reached, the estimation of inventory and removals proceeds to the next period.

DATA

The forest survey in Virginia conducted by USDA Forest Service in 1984 provides the initial inventory data for TRIM. These data were aggregated by ownership, species, and site class at the state level. The ownership categories include National Forest, Other Public, Forest Industry, Farmer, Private Corporate, and Private individual. Species include pine plantation, natural pine, mixed pine-hardwoods, upland hardwoods, and bottomland hardwoods. Only softwood species were considered in this study. The site class includes high site, medium site, and low site.

The standard yield tables of 5-year age class for each species, site quality, and management intensity were developed empirically from the average conditions observed on selected survey plots (McClure and Knight 1984). The thinning and mortality tables were also estimated from the selected survey plots (Brown 1986).

RESULTS

Several assumptions were made before performing sensitivity analyses. First, the timberland area remains unchanged during the projected period. This assumption can be relaxed by assigning the change information to TRIM. Second, the impact estimates are the difference between inventory levels with and without changes in crown length. Since changes in crown length might partly result from natural pruning and artificial pruning, this study excludes this possibility except for the atmospheric deposition impact. Third, substitution between softwood and hardwood or among ownerships is independent. Harvest request for softwood is allocated to softwood stands only. Harvest request for one ownership is only allocated to those stands that belong to this ownership. So one can project inventory for softwood or hardwood only. TRIM already has this assumption in the algorithms. Finally, regeneration does not change species and growth conditions after harvesting. Also, there is no delay for regeneration after harvesting.

IMPACT ON INVENTORY AND REMOVALS

First, the existing forecasts of timber removals from all ownerships based on USDA Forest Service projection were used for the analysis. Table 20 provides this information. The sensitivity analysis was performed by reducing crown length at different levels. The reductions of crown length are 1, 5, and 10 feet. From equation [3], it can be shown that 1-foot, 5-foot, and 10-foot reductions of crown length can cause 0.63, 3.1, and 6.3 percent reduction of volume per acre in the whole yield table. So the yield tables in TRIM can be modified accordingly for each level of crown length reduction. Table 21 shows the proportion change of averaged crown length in each 5-year age class for each crown length reduction level. These proportion changes are not much different between age classes.

TRIM can be run separately for each ownership or a group of ownerships. Due to the nature of the existing forecasts and the timber removals model, the sensitivity analysis was performed separately for each of National Forest, Other Public, Forest Industry, and Other Private. The projection period is 1990-2035. In this analysis, the harvest request was assumed to be filled and identical to the analysis applied to each level of crown length reduction. The harvest request based on Forest Service projection for Forest Industry exceeds the available harvest volume in several periods. The actual harvest volume is different between each analysis for level of crown length reduction if the harvest request exceeds the available volume. And the impact estimation will be biased. An estimate of harvest request based on the past trend for Forest Industry was used. The value used for this harvest request is 50 million cubic feet and so the harvest request can be filled. These results are shown in Tables 22, 23, 24, and 25, respectively.

Table 22 shows the sensitivity analysis for the impact of crown length reduction on forest inventory for National Forest based on Forest Service projection of timber removals. The inventory projection without crown length reduction indicates that the estimated removals are less than the net growth volume and so the inventory level goes up with time. A one-foot reduction of crown length causes 0.6 to 0.7 percent reduction in the projected inventory. A five-foot reduction of crown length causes 0.9 to 1.5 percent reduction in the projected inventory. A ten-foot reduction causes 3.5 to 4.5 percent reduction in the inventory. This percentage reduction of inventory increases slightly with time and obviously with the crown length reduction level. Also, this percentage reduction is far less than the percentage reduction in the yield tables (see Table 30). Part of the reason is that the estimated removals are less than the net growth volume, so the increases in inventory can offset the effect of the yield table reduction.

Table 23 shows the sensitivity analysis for the impact of crown length reduction on forest inventory for Other Public based on Forest Service projection of timber removals. The baseline inventory projection value indicates that the estimated removals are greater than the net growth volume and so the inventory level goes down with time. A one-foot reduction of crown length causes 0.6 to 1.2 percent reduction in the inventory. A five-foot reduction causes 3.1 to 6.0 percent reduction in the inventory. A ten-foot reduction causes 5.4 to 10.9 percent reduction in the inventory. The percentage reduction of inventory increases with time and the crown length reduction level. Also, this percentage reduction is greater than the yield table reduction.

Table 24 shows the sensitivity analysis for the impact of crown length reduction on forest inventory for Forest Industry based on 50 million cubic feet of timber removals. The inventory projection without crown length reduction indicates that these estimated timber removals are greater than the net growth volume and the inventory level goes down. A one-foot crown length reduction causes 0.6 to 1.2 percent reduction of the inventory. A five-foot crown length reduction causes 3.0 to 6.0 percent reduction of the inventory. A ten-foot crown length reduction causes 5.4 to 12.0 percent reduction of the inventory. The relative reduction of inventory increases with crown length reduction and time. Also, this relative reduction in inventory is greater than the relative reduction of the yield tables.

Table 25 shows the sensitivity analysis for the impact of crown length reduction on forest inventory for Other Private based on Forest Service projection of timber removals. The inventory projection without crown length reduction indicates that these estimated removals are greater than the net growth volume and the inventory level goes down with time. A one-foot crown length reduction causes 0.3 to 1.7 percent reduction of the inventory. A five-foot crown length reduction causes 2.0 to 8.7 percent reduction of the inventory. A ten-foot crown length reduction causes 4.4 to 17.8 percent reduction of the inventory. This percentage reduction increases with time and crown length reduction level.

In summary, the impact estimation using USDA Forest Service's removals estimate shows that the relative reduction in inventory depends on crown length reduction level. The larger the crown length reduction, the greater the relative decrease of inventory. The relative decrease of inventory may increase with time and harvest volume. Also, this relative reduction of inventory is slightly greater than the yield table reduction.

Next, equations [4] and [5] were used with TRIM to approximate the interactions between timber removals and inventory levels. Sensitivity analysis including these interactions might have different results. The linking of equation [4] with TRIM can be made using the start-up procedure. This start-up procedure can apply to each projection period simultaneously, provided that the estimated and projected timber removals are close to each other. The number of iterations will not be too large to obtain two-place accuracy if a bisection search method is used to update the estimated value. Since the linkage is possible, one can estimate the impact on inventory and removals also.

The linking of equation [5] with TRIM is straightforward once the timberland area information is known from TRIM. Since timberland area is assumed constant, the timber removals from Other Private ownership vary only with the price variable and are not affected by the inventory level. So the impact estimation is only for inventory level on Other Private. The price expectation model [6] combined with the previous price information is used to generate a periodic weighted price series.

Table 26 shows these projected timber removals from Forest Industry and Other Private using equations [4] and [5], and TRIM. The model estimate for Forest Industry is less than one half of timber removals based on Forest Service projection. This large difference between these two projections results from the method of projection. The projection method used by Forest Service was assumed that the softwood timberland area in Virginia would be increased significantly in the near future. So the Forest Service projection is over-estimated according to this initial inventory data. The model estimate for Other Private is close to those Forest Service projection.

Table 27 shows the sensitivity analysis for the impact of crown length reduction on timber removals from Forest Industry. The removals projection without crown length reduction indicates the trend of increasing harvest volume during the projected period. A one-foot reduction of crown length causes 0.5 percent reduction of the removals. A five-foot reduction causes 2.5 percent reduction of the removals. A ten-foot reduction causes 4.3 to 5.4 percent reduction in the removals. The percentage reduction is nearly linear with the crown length reduction level. The impact on timber removals might be the result from the stumpage supply shift. Private forest owners tend to reduce harvest volume when the available inventory becomes short. Also, cost of timber production increases when forest productivity decreases. On the other hand, the inventory level depends on the harvest volume. Less harvest volume can ameliorate the decrease of inventory due to atmospheric deposition impacts.

Table 28 shows the sensitivity analysis for the impact of crown length reduction on forest inventory for Forest Industry considering the interactions between removals and inventory levels by equation [4] and TRIM. The inventory projection without crown length reduction indicates that the net growth volume during the period 1985-1995 is less than the estimated harvest volume but greater in the remaining period. This suggests that the stand age composition in the initial inventory was young and so the corresponding growth is small. When these young stands grow older, the available volume becomes larger. A one-foot reduction of crown length causes 0.6 to 0.7 percent reduction in the inventory. A five-foot reduction causes 2.8 to 3.2 percent reduction in the inventory. A ten-foot reduction causes 5.2 to 6.4 percent reduction in the inventory. The percentage reduction of inventory increases slightly with time and nearly linearly with the crown length reduction level. Also, this percentage reduction is close to the yield table reduction.

Table 29 shows the sensitivity analysis for the impact of crown length reduction on forest inventory for Other Private using model estimate of timber removals. The inventory projection without crown length reduction indicates that the estimated harvest volume is greater than the net growth volume and so the inventory level goes down with time. The overall percentage reduction of inventory level is similar to that in Table 25.

Table 30 shows the summarized statistics of crown length reduction impact on the yield table, inventory, and removals during the projection period. The percentage reduction in the yield table is obtained from equation [3]. The averaged reduction of inventory for all ownerships is slightly greater than the yield table reduction. If one could develop a workable timber removals model for each ownership just as the model [4] for Forest Industry, then the reduction of inventory level would be less. The average reduction of timber removals from Forest Industry is less than the yield table reduction.

In summary, the overall impact estimation depends on the crown length reduction level. The larger the crown length reduction, the greater the inventory reduction. Also, the reduction of inventory increases with time and harvest volume in most cases. The overall percentage reduction of inventory is larger than that of the yield tables due to the crown length reduction, while the percentage reduction of removals is slightly less than that. The actual harvest volume is mostly determined by the market force. In the long run, the demand for the stumpage will go up but the supply of timber depends on the production cost and inventory available. For this reason, the interactions between removals and inventory levels should be considered in this impact estimation.

DISCUSSION AND SUMMARY

A decisionmaking framework consisting of a forest inventory projection model, a timber production model, and a timber removals model can be used to assess the regional impacts of atmospheric deposition on forest inventory and timber removals. The Timber Resource Inventory Model (TRIM) used initial inventory data and the associated yield tables and harvest requests to project future forest inventory. The timber production function allows the estimation of the individual influence of crown length on stand growth and yield. Since crown length can reflect atmospheric deposition impacts, this timber production function can be used to quantify atmospheric deposition impacts on timber output. The timber removals model was linked with TRIM to simulate the interactions between removals and inventory levels. The existing forecasts of timber removals were used as a supplement to the removals model estimates.

The use of the crown length elasticity implicitly assumes that the variation of crown length is independent of stand age, site quality, and stand density. Biologically, crown length is related to stand age, site quality, and stand density. So variation of crown length might affect, or be affected by, these factors. However, the value from the crown length elasticity can be used to partition this individual influence since this variable is not affected by collinearity. So, the impact estimation is possible even if this complementary relation between crown length and stand age, site quality, and stand density exists.

The linking of the timber removals model for Forest Industry with TRIM indicates that the relative impact estimation might be less when the interactions between removals and inventory is considered in the projection. Without considering this interaction, the impact estimation for inventory is only through atmospheric deposition impacts on stand growth and yield. However, when forest inventory is reduced to some extent, the timber supply may shift upward due to increase of production cost and decrease of inventory available. So the timber removals may be reduced and the projected inventory increases accordingly.

Recently, the Timber Assessment Market Model (TAMM) has been linked with TRIM(USDA Forest Service 1987a). This market model can reflect timber supply shifts and may be the best candidate econometric model. Since a regional projection of timber removals should include net exports from the region and the non-commercial clearings, additional projections are needed. Also TAMM projects only regional timber supply. For state level projection, additional work is needed to use this market model. The consumption function approach is a substitute for this market model to illustrate the interactions between removals and inventory.

Several assumptions were made before running TRIM. They were substitution between hardwood and softwood, substitution among ownerships, change of timberland area, harvest sequence, and the suitability of 5-year yield tables. Some of these assumptions are difficult to relax due to the algorithms rooted in TRIM. These at least include substitution between species and substitution among ownerships. However, these two assumptions make it possible to assess impacts for softwood only or for each ownership only in this study. Nevertheless, these assumptions might cause some additional error in the impact estimation. The primary forest product could be made either from hardwood or from softwood. The substitution becomes possible when prices between species or ownerships are different.

Use of 5-year yield tables instead of one-year yield tables might inflate the growth estimation error, especially for short rotation species. This error partly resulted from the aggregation of initial inventory data into 5-year age class basic resource units. The initial inventory data lost detailed age class information and the projection of growth becomes less reliable. To prevent this error, TRIM probably can use a one-year yield table by increasing its storage requirement on the computer. The use of 5-year yield table also forces TRIM to use a 5-year harvest request. The estimation of 5-year harvest volume is more difficult than the estimation of 1-year harvest volume using time series data.

If some econometric model is available, the start-up procedure is needed to integrate TRIM with this model. The use of this start-up procedure suggests that the inventory factor is an important variable in modeling a timber market function. Also, the use of harvest request to allocate harvest sequence indicates that TRIM is a volume-control regulation model. For those forested areas with area-control regulation, TRIM might not be suitable.

This decisionmaking framework can also be used to measure some silvicultural practice effects on regional inventory. As shown before, the site index variable is not affected by collinearity. Following the same procedure as the crown length elasticity formula, one can obtain a quantitative measure of site index increase on stand growth and yield. Many studies have shown that irrigation, fertilization, and drainage can improve site quality for a stand. So the benefit of these practices can be measured using this framework.

Table 19. SUR estimates and the associated standard error, t-value, variance inflation factor(VIF) and condition number(CN).

Parameter[1]	Estimate	Standard error	t-value	VIF	CN
a_1	-17.3589	0.6427	-27.01	9.56	1.00
a_2	0.0048	0.0005	10.70	9.31	1.32
a_3	-49.6134	3.4121	-14.54	1.23	1.86
a_4	0.0063	0.0015	4.28	1.20	6.24

1. **Equation form:** $\log(V) = a_0 + a_1 1/A + a_2 B + a_3 1/SI + a_4 Cl$

Table 20. Existing forecasts of softwood harvest request in Virginia based on Forest Service projection, by ownership, 1990-2030.

Ownership	1990	2000	2010	2020	2030
			(million cubic feet)		
National Forest	1	1	1	2	1
Other Public	7	9	9	8	7
Forest Industry[1]	72	78	84	93	90
Other Private	141	137	131	167	170

1. 50 is used in all periods in TRIM runs so harvest request is filled.

Table 21. Proportion change of average crown length in each 5-year age class for each level of crown length reduction.

Age class	Average crown length, ft	Crown length reduction, ft		
		1	5	10
			(proportion)	
5 - 10	14.16	0.071	0.353	0.706
11 - 15	16.60	0.060	0.301	0.602
16 - 20	16.36	0.061	0.306	0.611
21 - 25	16.16	0.062	0.309	0.619
26 - 30	16.23	0.062	0.308	0.616

Table 22. Impacts of crown length reduction on softwood inventory in Virginia for National Forest based on Forest Service removal projection, 1990-2035.

Year	Crown length reduction			
	0 foot	1 foot	5 feet	10 feet
	(million cubic feet)			
1990	237.036	235.502 (-.006)	234.934 (-.009)	228.561 (-.035)
1995	240.922	239.337 (-.007)	238.345 (-.011)	231.809 (-.037)
2000	242.058	240.419 (-.007)	239.309 (-.011)	232.616 (-.039)
2005	243.609	241.941 (-.007)	240.690 (-.012)	233.847 (-.040)
2010	245.308	243.616 (-.007)	242.216 (-.013)	235.218 (-.041)
2015	245.819	244.104 (-.007)	242.580 (-.013)	235.502 (-.042)
2020	246.799	245.079 (-.007)	243.411 (-.014)	236.234 (-.043)
2025	246.089	244.364 (-.007)	242.606 (-.014)	235.408 (-.043)
2030	246.954	245.218 (-.007)	243.321 (-.015)	236.075 (-.044)
2035	247.249	245.513 (-.007)	243.492 (-.015)	236.216 (-.045)

Note: The value in parenthesis indicates the proportion change compared to the value in column 2.

Table 23. Impacts of crown length reduction on softwood inventory in Virginia for Other Public based on Forest Service removal projection, 1990-2035.

Year	Crown length reduction			
	0 foot	1 foot	5 feet	10 feet
	(million cubic feet)			
1990	300.942	298.990 (-.006)	291.538 (-.031)	284.771 (-.054)
1995	293.042	290.971 (-.007)	282.941 (-.034)	275.576 (-.060)
2000	281.754	279.544 (-.008)	271.023 (-.038)	262.951 (-.066)
2005	268.530	266.182 (-.009)	257.174 (-.042)	248.345 (-.075)
2010	255.119	252.651 (-.009)	243.180 (-.047)	233.736 (-.084)
2015	242.126	239.598 (-.010)	229.841 (-.051)	219.860 (-.092)
2020	230.006	227.405 (-.011)	217.366 (-.055)	206.833 (-.101)
2025	221.184	218.530 (-.012)	208.269 (-.058)	197.554 (-.096)
2030	216.250	213.562 (-.012)	203.195 (-.060)	192.672 (-.109)
2035	215.674	213.124 (-.012)	203.334 (-.057)	193.116 (-.105)

Note: The value in parenthesis indicates the proportion change compared to the value in column 2.

Table 24. Impacts of crown length reduction on softwood inventory in Virginia for Forest Industry based on the past trend of removals, 1990-2035.

Year	Crown length reduction			
	0 foot	1 foot	5 feet	10 feet
	(million cubic feet)			
1990	1041.877	1035.198 (-.006)	1010.893 (-.030)	985.638 (-.054)
1995	826.943	820.442 (-.008)	796.734 (-.036)	775.586 (-.062)
2000	784.366	776.672 (-.010)	748.466 (-.046)	716.541 (-.086)
2005	769.809	760.943 (-.012)	728.047 (-.054)	689.993 (-.104)
2010	781.012	771.234 (-.012)	734.402 (-.060)	690.181 (-.116)
2015	818.726	808.373 (-.012)	769.054 (-.061)	721.124 (-.119)
2020	880.543	869.748 (-.012)	828.127 (-.060)	774.980 (-.120)
2025	952.694	941.238 (-.012)	896.878 (-.060)	838.134 (-.120)
2030	1031.674	1019.443 (-.012)	972.442 (-.060)	908.400 (-.120)
2035	1108.416	1095.527 (-.012)	1045.874 (-.060)	979.712 (-.120)

Note: The value in parenthesis indicates the proportion change compared to the value in column 2.

Table 25. Impacts of crown length reduction on softwood inventory for Other Private based on Forest Service removal projection, 1990-2035.

Year	Crown length reduction			
	0 foot	1 foot	5 feet	10 feet
	(million cubic feet)			
1990	3200.532	3190.387 (-.003)	3133.334 (-.020)	3057.459 (-.044)
1995	3074.630	3060.833 (-.004)	2993.491 (-.026)	2901.746 (-.056)
2000	2961.298	2944.222 (-.005)	2865.398 (-.032)	2757.755 (-.068)
2005	2886.666	2866.312 (-.007)	2774.592 (-.039)	2650.093 (-.083)
2010	2841.904	2818.519 (-.008)	2716.363 (-.044)	2576.486 (-.093)
2015	2821.494	2794.964 (-.009)	2684.310 (-.049)	2532.701 (-.102)
2020	2722.812	2692.820 (-.011)	2574.630 (-.054)	2411.934 (-.114)
2025	2523.987	2491.263 (-.013)	2367.709 (-.062)	2198.760 (-.130)
2030	2346.451	2310.938 (-.015)	2174.045 (-.073)	1991.149 (-.151)
2035	2183.377	2144.931 (-.017)	1993.831 (-.087)	1794.081 (-.178)

Note: The value in parenthesis indicates the proportion change compared to value in column 2.

Table 26. Forecasts of softwood timber removals in Virginia for Forest Industry and Other Private based on timber removals models and TRIM's projection, 1990-2035.

Year	Forest Industry	Other Private
	(million cubic feet)	
1990	30.821	131.167
1995	31.313	138.432
2000	33.271	140.863
2005	34.601	141.980
2010	35.505	142.225
2015	36.493	142.302
2020	37.610	142.332
2025	38.871	142.332
2030	40.425	142.332
2035	42.039	142.332

Table 27. Impacts of crown length reduction on timber removals in Virginia for Forest Industry based on TRIM and the timber removals model, 1990-2035.

Year	Crown length reduction			
	0 foot	1 foot	5 feet	10 feet
		(million cubic feet)		
1990	30.821	30.665 (-.005)	30.052 (-.025)	29.495 (-.043)
1995	31.313	31.154 (-.005)	30.503 (-.025)	29.965 (-.043)
2000	33.271	33.100 (-.005)	32.372 (-.027)	31.611 (-.049)
2005	34.601	34.423 (-.005)	33.636 (-.027)	32.775 (-.053)
2010	35.505	35.323 (-.005)	34.505 (-.028)	33.598 (-.053)
2015	36.493	36.304 (-.005)	35.465 (-.028)	34.514 (-.054)
2020	37.610	37.414 (-.005)	36.555 (-.028)	35.559 (-.054)
2025	38.871	38.663 (-.005)	37.781 (-.028)	36.719 (-.055)
2030	40.425	40.205 (-.005)	39.290 (-.028)	38.289 (-.053)
2035	42.039	41.807 (-.005)	40.854 (-.028)	39.747 (-.054)

Note: The value in parenthesis indicates the proportion change compared to the value in column 2.

Table 28. Impacts of crown length reduction on softwood inventory in Virginia for Forest Industry based on model's removal projection, 1990-2035.

Year	Crown length reduction			
	0 foot	1 foot	5 feet	10 feet
	(million cubic feet)			
1990	1016.197	1010.234 (-.006)	987.106 (-.028)	963.213 (-.052)
1995	855.475	850.298 (-.006)	830.297 (-.029)	812.766 (-.050)
2000	865.915	860.365 (-.006)	839.308 (-.030)	814.523 (-.059)
2005	883.126	877.195 (-.006)	855.005 (-.031)	828.230 (-.062)
2010	905.025	898.796 (-.006)	875.741 (-.032)	847.147 (-.063)
2015	932.711	926.243 (-.007)	902.462 (-.032)	872.450 (-.064)
2020	965.208	958.557 (-.007)	934.017 (-.032)	902.890 (-.064)
2025	1002.726	995.870 (-.007)	970.391 (-.032)	938.313 (-.064)
2030	1049.252	1042.207 (-.007)	1015.549 (-.032)	981.654 (-.064)
2035	1097.998	1090.711 (-.006)	1062.801 (-.032)	1027.368 (-.064)

Note: The value in parenthesis indicates the proportion change compared to the value in column 2.

Table 29. Impacts of crown length reduction on softwood inventory in Virginia for Other Private based on model's removal projection, 1990-2035.

Year	Crown length reduction			
	0 foot	1 foot	5 feet	10 feet
	(million cubic feet)			
1990	3233.131	3222.781 (-.003)	3166.437 (-.020)	3089.936 (-.044)
1995	3120.116	3106.100 (-.004)	3039.442 (-.026)	2947.012 (-.055)
2000	2992.885	2975.604 (-.005)	2897.631 (-.032)	2789.497 (-.068)
2005	2886.699	2866.231 (-.007)	2775.454 (-.039)	2650.653 (-.083)
2010	2797.757	2774.294 (-.008)	2672.627 (-.045)	2532.407 (-.095)
2015	2724.457	2697.912 (-.010)	2587.623 (-.050)	2436.086 (-.106)
2020	2661.385	2631.415 (-.011)	2513.546 (-.056)	2350.755 (-.116)
2025	2594.739	2562.043 (-.013)	2438.924 (-.060)	2270.440 (-.125)
2030	2555.918	2520.905 (-.014)	2385.967 (-.066)	2204.785 (-.137)
2035	2519.922	2482.863 (-.015)	2337.217 (-.075)	2141.897 (-.150)

Note: The value in parenthesis indicates the proportion change compared to the value in column 2.

Table 30. Summarized results of crown length reduction impact on yield tables, inventory, and removals in Virginia, 1990-2035.

Reduction in crown length, feet	Change in yield table, proportion	Change in[1] inventory, proportion	Change in[2] removals, proportion
1	-.006	-.009	-.005
5	-.031	-.043	-.027
10	-.063	-.088	-.052

1. Based on Forest Service removals projection.

2. This proportion change of removals is only for Forest Industry.

Chapter 7

SUMMARY AND CONCLUSIONS

SUMMARY

A decisionmaking framework was developed to assess atmospheric deposition impacts on softwood inventory in Virginia during the years 1990-2035. This decisionmaking framework consists of three segments: a timber inventory projection model, a timber production function, and a timber removals model. The Timber Resource Inventory Model (TRIM) used the initial inventory data and the corresponding stand growth and yield and harvest volume information to project future forest inventory. The timber production function allows the estimate of individual influence of the crown length variable on stand growth and yield for softwood species. The timber removals model was linked with TRIM to simulate the interactions between timber removals and inventory levels.

The feasibility of TRIM for projecting atmospheric deposition impacts was examined. The major algorithms that simulate harvest, regeneration, and inventory computation were analyzed. No algorithm which simulates, in an analytical sense, atmospheric deposition impacts exists in

TRIM. Sensitivity analysis and an *a priori* analysis were used to identify the candidate variables that can obviously reflect atmospheric deposition impacts. Growth and harvest decision variable changes apparently affect the projected inventory. It is concluded that TRIM could be used for impact projection if exogenous modification of growth and harvest decision variables was undertaken.

A timber production function approach was used to develop a yield equation for loblolly pine plantations in the Southeastern region. Following Schumacher's yield model, the yield equation established the logarithm of timber output as a function of the reciprocal of stand age and some measure of site quality, stand density, and crown length. The selection of functional form and predictor variables depends on goodness-of-fit, biological rationale, and minimum collinearity. By statistical analysis, the yield equation was fitted with remeasurement data using differentiation and integration methods. Also, a system of predictor equations was added to this yield equation and seemingly unrelated regressions was used to ameliorate serial correlation within this equation system. The input-output and input-input relationships from the yield equation were derived in terms of cross partial derivatives of output with respect to pairs of input variables, partial elasticities of output with respect to each input variable, and elasticities of substitution between pairs of input variables. The value from the crown length elasticity was used to quantify atmospheric deposition impacts on stand growth and yield, since the corresponding variance inflation factor is small and crown length is assumed to reflect atmospheric deposition impacts on stand growth. This input-output information was used to modify the growth variables in TRIM.

Modification of the harvest decision variables were not directly related to atmospheric deposition impacts but indirectly through the interactions between removals and inventory. A consumption function approach was used to estimate the harvest request for softwood species. The consumption function assumed that timber removals were a function of inventory level, timberland area, and stumpage price. The Box-Cox transformation, the stepwise regression procedure, and the standard error criterion were used to determine the functional form of the timber removals model for each ownership category. Also, a price expectation model was developed for the removals models to generate a future price series.

The integration of TRIM, the timber production function, and the timber removals model was made to form the decisionmaking framework. The linking of the timber production function with TRIM was done by modifying the yield tables in TRIM according to the calculated partial elasticity. The timber removals models for Forest Industry and Other Private were linked with TRIM to simulate the interactions between removals and inventory. The linking of TRIM with the timber removals model needs some start-up procedure. This start-up procedure requires iterations between TRIM and a timber removals model if the inventory variable having a positive sign is included in the timber removals model. The timber removals model for Other Private ownership can work with TRIM without iterations, since no inventory variable is in this model. The removals models for National Forest and Other Public can not link with TRIM because of the negative sign for the inventory variable within these two models. The existing forecasts of timber removals based on a Forest Service projection are a supplement to the removals model estimates.

This decisionmaking framework was applied to the softwood inventory data in Virginia. Sensitivity analysis was used to examine the impacts of crown length reduction by 1, 5, and 10 feet on forest inventory and timber removals for the years from 1990-2035. The impact estimation was based on the difference between inventory levels with and without crown length reduction. Results show that the impact estimation depends on the crown length reduction level. The percentage reduction of inventory increases with the crown length reduction level. If the interactions between timber removals and inventory levels are considered, this percentage reduction could be smaller. On average, the percentage reduction of inventory is slightly greater than the yield table reduction due to the crown length reduction.

The approximation of the impacts on timber removals is possible only for the Forest Industry. The percentage reduction of timber removals is nearly linear with the crown length reduction level. On average, this percentage reduction is slightly less than the percentage reduction of the yield table due to crown length reduction.

CONCLUSIONS

It is possible to develop a decisionmaking framework for policy decisionmakers to assess changes in regional forest inventory in response to possible levels of atmospheric deposition. TRIM is feasible for projecting atmospheric deposition impact on inventory if the growth and harvest decision variables are modified according to some exogenous biological and economic information. The developed timber production function allows a quantitative measure of individual influence of crown length reduction on stand growth and yield. This is the key information for impact estimation. The developed timber removals model can be linked with TRIM unless the inventory variable has a negative sign.

The crown length variable plays a key role in this impact estimation. Crown length is one of stand characteristics that reflect environmental impacts on stand growth and yield. Modification of crown length could reflect change in photosynthetic efficiency. Since photosynthesis may be affected by atmospheric deposition, this modification of crown length could reflect atmospheric deposition impacts on stand growth and yield. The partial elasticity of crown length derived from the timber production function gives this quantitative measure of atmospheric deposition impacts on the yield table. Modification of yield tables in TRIM gives TRIM's feasibility for impact assessment.

Since the crown length and site index variables are not affected by collinearity, the corresponding input-output and input-input relationships can provide some guidelines in forest management and silvicultural practices. The complementary relationships among crown length, age, stand density, and site quality suggest that the longer the crown length or the better the site quality, the greater the forest productivity. Any silvicultural practices that can improve crown length growth or site quality should help increase stand growth and yield. These practices include precommercial and commercial thinning, fertilization, irrigation, and drainage. Given this information, this decisionmaking framework can be used to measure silvicultural practice effects on regional inventory. Also, crown length can serve as an index to assess potential productivity of a stand. The longer the average crown length, the more vigorous the stand.

Atmospheric deposition could affect stand growth through four types of injury: growth loss, mortality, increased susceptibility to second any stress, and visible injury. Modification of yield tables can reflect most of these impacts. The overall percentage reduction of inventory level depends on crown length reduction level. The relative change in physical inventory is slightly larger than the relative change in the yield tables due to the crown length reduction. Less harvest volume can mitigate this reduction. Since inventory level is a major supply shifter, the interaction between inventory and removals could also mitigate this reduction. The relative impact on timber removals is slightly less than the relative impact on the yield tables due to the crown length reduction. This study concludes that the quantitative information of environmental impacts on stand growth and yield can be used to judge the overall relative change in physical inventory and timber removals. The impact estimation eventually relies on the scientific study of the environmental impacts on stand growth and yield.

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Appendix A

NOTATION

Table 31. Notation list for Chapter 3.

APLIM	=	the maximum proportion of stocking allowed
AVDIAM	=	the average diameter for each management intensity
CNOR	=	the current normality
COEFAP	=	the intercept of the approach-to-normality equation
CT	=	the commercial thinning
FPNOR	=	the projected normality used to calculate growth
FULLAP	=	the last age class to receive the full increase in growth
GROTYP	=	the flag to indicate the yield projection method
Ha	=	the available harvest volume
HALFAP	=	the last age class to receive one half of the increase of growth
HARGRO	=	the adjusted factor for growth on harvest
Hc	=	the harvest volume from converting
Hex	=	the exogenous harvest volume
Hen	=	the endogenous harvest volume
Hr	=	the harvest request
HRVACU	=	the harvest request
Ht	=	the total harvest volume
HVPROP	=	the preferred harvest proportion for each age class
INTAP	=	the slope of the approach-to-normality equation
MINHAR	=	the minimum harvest age class
MORTPA	=	the mortality volume per acre in the mortality table
MORPRP	=	the proportion of the salvage volume
MORVOL	=	the minimum amount of salvage volume
MS	=	the mortality salvage
ODSTOC	=	the stocking level for each donor category upon entry into timberland
PNOR	=	the projected normality
ROT	=	the rotation age
SLDIST	=	the stocking level distribution of acres regenerated
SLMID	=	the stocking level midpoint
THINPA	=	the thinning volume per acre in the thinning table
Vi	=	the volume in age class i
VOLPA	=	the volume per acre in the yield table

Table 32. Notation list for Chapter 4.

A	=	the stand age
A_0	=	the initial stand age
B	=	the basal area per acre
B_0	=	the initial basal area per acre
Cl	=	the crown length
CN	=	the condition number
Cr	=	the crown ratio
CS_0	=	the initial crown size
E	=	the elasticity of scale
$E_{(V,A)}$	=	the elasticity with respect to age
$E_{(V,B)}$	=	the elasticity with respect to basal area
$E_{(V,SI)}$	=	the elasticity with respect to site index
$E_{(V,Cl)}$	=	the elasticity with respect to crown length
$E_{(A,B)}$	=	the elasticity of substitution between age and basal area
$E_{(A,SI)}$	=	the elasticity of substitution between age and site index
$E_{(A,Cl)}$	=	the elasticity of substitution between age and crown length
$E_{(B,SI)}$	=	the elasticity of substitution between basal area and site index
$E_{(B,Cl)}$	=	the elasticity of substitution between basal area and crown length
$E_{(SI,Cl)}$	=	the elasticity of substitution between site index and crown length
f(SD)	=	the function of stand density
f′(SD)	=	the derivative of f(SD)
FI	=	the fit index
g(SQ)	=	the function of site quality
g′(SQ)	=	the derivative of g(SQ)
h(CS)	=	the function of crown size
h′(CS)	=	the derivative of h(CS)
Hd	=	the average dominant stand height
Hd_0	=	the initial dominant stand height
log(V)	=	the natural logarithm of volume per acre
MD	=	the mean difference of the actual and estimated values
OLS	=	the ordinary least squares
SD_0	=	the initial stand density
SE	=	the standard error of the differences between actual and estimated values
SI	=	the site index based on the age 25
SUR	=	the seemingly unrelated regressions
3SLS	=	the three-stage least squares
VIF	=	the variance inflation factor
V_0	=	the initial stand volume per acre

Table 33. Notation list for Chapter 5.

A_{ij}	=	the timberland area on ownership i and species j
DW	=	the Durbin-Watson's statistics
F_{ij}	=	the final goods price for ownership i and species j
FI	=	Forest Industry
FP	=	Other Private
I_{ij}	=	the inventory available for ownership i and species j
L(r)	=	the concentrated likelihood function
NF	=	National Forest
OP	=	Other Public
P_{ij}	=	the stumpage price for ownership i and species j
Q^s_{ij}	=	the stumpage supplied from ownership i and species j
Q^d_{ij}	=	the stumpage demand for ownership i and species j
r	=	the parameter used to determine the functional form
RSS(r)	=	the residual sum of squares with r at the chosen value
R^2	=	the multiple correlation coefficient
SE	=	the standard error
TR_{ij}	=	the timber removals from ownership i and species j
TRIM	=	the Timber Resource Inventory Model

Table 34. Notation list for Chapter 6.

A	= the stand age
Ai	= the timberland area on ownership i
B	= the basal area per acre
Cl	= the crown length
CN	= the condition number
DW	= the Durbin-Watson's statistics
$E_{(v,cl)}$	= the elasticity with respect to crown length
FI	= Forest Industry
FP	= Other Private
NF	= National Forest
OP	= Other Public
Pt	= the timber price at year t
R^2	= the multiple correlation coefficient
SE	= the standard error
SI	= the site index
SUR	= the seemingly unrelated regressions
TAMM	= the Timber Assessment Market Model
TPF	= the timber production function
TRi	= the timber removals from ownership i
TRIM	= the Timber Resource Inventory Model
TRM	= the timber removals model
V	= the volume per acre
VIF	= the variance inflation factor

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