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Modelling Growth and Yield for Intensively Managed Forests

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ABSTRACT : Growth and yield prediction methods, ranging from whole-stand models to individual-tree models, have been developed for forest types managed for wood production. The resultant models are used for a host of purposes including inventory updating, management planning, evaluation of silvicultural alternatives, and harvest scheduling. Because of the large investment in developing growth and yield models for improved genotypes and silvicultural practices for loblolly pine (*Pinus taeda*) in the Southern United States, this region serves to illustrate approaches for modelling intensively managed forests. Analytical methods and computing power generally do not restrict development of reliable growth and yield models. However, long-term empirical observations on stand development, which are time consuming and expensive to obtain, often limit modelling efforts. Given that growth and yield models are used to project present volumes and to evaluate alternative treatment effects, data of both the inventory type and the experimental type are needed. Data for developing stand simulators for loblolly pine plantations have been obtained from a combination of permanent plots in operational forest stands and silvicultural experiments; these data collection efforts are described and summarized. Modelling is essential for integrating and synthesizing diverse information, identifying knowledge gaps, and making informed decisions. The questions being posed today are more complex than in the past, thus further accentuating the need for comprehensive models for stand development.

Keywords : Forest stand development, Measurements, Biometrics, Silviculture, Inventory, Management, Loblolly pine, *Pinus taeda*

INTRODUCTION

The focus of this paper is on modelling growth and yield of forest stands that are managed for wood production. Due to the large investment in developing improved genotypes and silvicultural practices for pine plantation management in the Southeastern United States, I will rely on work from this region to illustrate approaches to growth and yield modelling. While the results obtained are specific to the southern pine region of the US, the methods developed to model a wide range of silvicultural inputs and utilization options should have broad applicability wherever intensive management is practiced.

Since the 1950's, the southern pine resource has changed from being essentially all natural stands to being more than half in planted stands today. The total area in pine type has remained roughly constant at around 28,000,000 hectares while the shift from natural to planted stands has occurred. Projections from the United States Department of Agriculture (1990) indicate that the proportion of area in the pine type in plantations will level off at around two-thirds by 2020. At present around half of the wood furnished for industry comes from fast-grown plantations. Because of the multitude of management decisions that must be made when practicing intensive silviculture, and the magnitude of the financial investment represented, a large amount of research has been focused on the southern pines and on loblolly pine (*Pinus taeda* L.) in particular.

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DEVELOPING GROWTH AND YIELD MODELS

Computing Technology

The revolution in computing technology has affected growth and yield modelling as it has all fields of science. Computing technology is now applied to capture data in the field, store and manage field data, estimate component equations, develop sophisticated stand simulators, and deliver numeric and visual output for a wide array of management and utilization options. Increased computing power has played a key role in advancing the science of forest growth and yield modelling.

Modelling Approaches

Forest management decision making is predicated on accurate forecast of growth and yield. While growth and yield forecasts enter into virtually all decisions, the uses of models can be broken down into the following general categories: inventory updating, management planning, evaluation of silvicultural alternatives, and harvest scheduling.

Growth and yield models produced to date can be categorized as follows: (1) whole-stand models: (a) aggregated values only, (b) size class information; (2) individual tree models: (a) distance-independent, (b) distance-dependent.

In the whole-stand approach, quantities such as volume, basal area, and/or number of trees per unit area are forecast. The basic input or predictor variables for these models for even-aged stands are generally age, site index, and stand density (numbers of trees planted per unit area for plantations; initial basal area for natural stands). Often only aggregated volume growth and/or yield is predicted for the total stand. As a variation on this approach, several researchers have applied probability density functions to estimate the number of trees by dbh (diameter at breast height) classes, given that an estimate of the total number per unit area is available. This approach, commonly termed the "diameter distribution approach," still relies on overall stand values as the basic modelling unit.

Approaches to predicting stand growth and yield that use individual trees as the modelling unit are referred to as "individual tree models." The components of tree growth (e.g., diameter increment, height increment) in these models are commonly linked through a computer program that simulates the growth of each tree and then aggregates these to provide estimates of stand growth and yield. Individual tree models are divided into two classes, distance-independent and distance-dependent, depending on whether or not individual tree locations are used. Distance-independent models project tree growth either individually or by size classes, usually as a function of present size and stand level variables (e.g., age, site index, number of trees per unit area). In distance-dependent models, initial stand conditions are input or generated and each tree is assigned a coordinate location. The growth of each tree is predicted as a function of its attributes, the site quality, and a measure of competition from neighbors. Additional information about growth and yield modelling approaches in common use can be found in the books by Avery and Burkhart (2002, chapter 17), Clutter et a1. (1983, chapter 4), Davis et al. (2001, chapter 5), Gadow and Hui (1999), and Vanclay (1994).

A wide variety of growth and yield models have been developed. No single model can be expected to be best for all purposes. In choosing a growth and yield model one must be concerned with the stand detail needed for the particular decision at hand and the efficiency in providing this information. In situations where predictions are required for a very broad range of management decisions, it would be desirable to have a system of growth and yield models capable of providing logical and consistent estimates for varying degrees of stand detail (whole-stand values, size class data, or individual tree information), thus allowing users to efficiently compute estimates with stand detail appropriate to the use of the information.

Daniels and Burkhart (1988) presented an initial framework for a system of integrated stand models for loblolly pine. Their model is a "telescoping" system in which a highly detailed overall stand model is developed and its components are "collapsed" around this common structure to provide structurally compatible models at each lower stage of resolution. This integrated system ranges from an individual tree, distance-dependent model to a whole-stand model.

Disaggregation is an alternate approach to integrated stand models. In this approach, overall stand volume, basal area, and other characteristics are the primary quantities predicted, and these quantities are disaggregated into size class or possibly individual tree information. The disaggregation approach has the advantage that volumes at all levels are conditioned on the whole-stand value (which is mathematically more tractable than size class or individual tree volumes), but it has the disadvantage that management treatment effects may not be readily incorporated at the whole-stand level. Both approaches -- telescoping (or aggregation) and disaggregation -- have advantages and disadvantages. Ritchie and Hann (1997) provide an overview of disaggregation methods that have been applied to forest growth and yield models.

Data Needs

The typical approach taken in past growth and yield studies was to define a population of interest, obtain a sample from the defined population (the sample could consist of temporary plots, permanent plots, or both), and estimate coefficients (invariably with least squares) in specified equation forms. This approach produces satisfactory prediction tools for many purposes, but it may not be adequate in circumstances where forest management practices and objectives are rapidly changing. Given that growth and yield models are used to project the present forest resource and to evaluate alternative treatment effects, data of both the inventory type (which describe operational stands of interest) and the experimental or research type (which describe response to treatment) are needed. The amount of effort that should be devoted to each type of data collection is not immediately obvious. Nor is it at all clear whether the data should be combined and a single model produced or the data kept separate and different models produced for different uses or objectives.

Curtis and Hyink (1984) provide an overview of data collection alternatives for growth and yield modelling, giving the relative merits of different types of data. Permanent plots established in the past have sometimes had limited usefulness because of inadequacies in the measurements taken. In any new permanent growth plots, I feel that the minimum data measurements should include dbh, height (on all trees), crown measures, stem quality assessment, and tree spatial locations.

The most pressing data needs are for permanent plots in operational forest stands and for designed experiments. I will describe data collection efforts in loblolly pine plantations to illustrate studies with these two types of data collection.

Field Studies for Growth and Yield Modelling

We have employed a combination of permanent sample plots in operational stands and designed experiments to provide the data base needed to construct robust growth and yield models for estimating response to a wide range of management inputs.

PLOTS IN OPERATIONAL STANDS

Regionwide Thinning Study

During the 1980-81 and 1981-82 dormant seasons, permanent plots were established at 186 locations throughout the natural range of loblolly pine (Burkhart et al. 1985). To be included in the sample the plantations had to meet the following specifications: they had to be at least eight years in age (defined as years since planting), unthinned, free of evidence of heavy disease or insect attack, not heavily damaged by ice or wind storms, free of interplanting, unpruned, not fertilized within the last four years, not planted with genetically improved stock, contain a minimum of 500 to 750 planted pine stems per ha which appear "free to grow," not more than 25% of the main canopy composed of volunteer pines, and established on a cutover area that received "typical"site preparation treatment for the site conditions and time at which the plantation was established.

In each qualifying plantation, a set of three comparable but not necessarily contiguous plots was established. To be judged "comparable" the maximum divergence in site index could not exceed 1.5 m (25-year base). Initial stocking was considered comparable if the maximum spread in trees per ha did not exceed 250 and the range in basal area did not exceed 4.6 m2 per ha for the three plots. When determining trees and basal area per unit area, all planted loblolly plus volunteer pines in the main canopy were used. However, the proportion of volunteer pines to planted loblolly was required to be similar on the three plots. Each plot was randomly assigned to a treatment category: (l) light thinning, (2) heavy thinning, or (3) control. A minimum buffer of at least two rows or 6 m (whichever was larger) was established around each plot, shielding it from all roads, windrows, or other stand openings. The control plots were generally around 0.04 ha in size, while the thinning plots ranged from 0.08 to 0.1 ha.

The location and stand history were recorded for each plot. Stand history included type of stand prior to the current plantation, when clearcut, type of site preparation, when planted, whether or not released, and other pertinent information. In addition, number of trees planted and age were determined.

The following data were recorded for all planted pines: dbh to the nearest 0.25 cm, total height to the nearest 0.3 m, height to the base of the live crown, crown class, and a stem quality assessment.

In addition to the data recorded on the planted pine, the following information was recorded for natural pine and hardwoods in the main canopy: dbh, total height, and species. All measured trees (planted pine, natural pine, and hardwoods) in the main canopy were individually numbered and tagged at dbh. A stem map showing the spatial location of all numbered and tagged trees was developed. Natural pine and hardwood trees not in the main canopy, but greater than 1.25 cm in dbh, were tallied by 2.5 cm dbh classes only.

These plots were remeasured seven times at three-year intervals. At the conclusion of the study, data on coarse woody debris were collected from stems that had been dead for varying lengths of time and additional information on wood quality was obtained by felling sample trees.

Regionwide Study in Intensively Managed Plantations

About five years before the termination of the first regionwide study in operational plantations, we planned and started installing a new study to represent the types of stands that would supply much of the wood in the next period. The next generation of plantations was established with genetically improved seedlings and received vegetation control and fertilizer applications as needed.

During the period 1996-2000, 170 permanent plot locations were established in 3-8 year-old intensively managed loblolly pine plantations across the natural loblolly pine growing region in the Piedmont, Atlantic Coastal Plain, and Gulf Coastal Plain areas. The plantations containing these plot locations are representative of current management and silvicultural practices. All received site preparation and vegetation control treatment appropriate for the site, were planted with genetically improved stock suitable for the locale, and have received operationally applied fertilization and competition control treatments as needed. Each plot was measured at establishment and subsequently on a 2-year cycle (Amateis et al. 2006).

Three plots were established at each location. When the stands reach 12 to 14 meters in height, treatments are imposed. One plot remains as an unthinned control, one plot receives a light thinning treatment and the third plot is assigned a heavy thinning treatment with all of the residual crop trees being pruned. Plot measurements are similar to those described for the first regionwide study in operational stands.

INCORPORATING SILVICULTURAL TREATMENTS

In addition to thinning, which is part of our regionwide permanent plot installations in operational stands, we have utilized data from designed experiments to enhance and expand our capabilities for forecasting growth and yield for a variety of management treatments.

Spacing Trials

Because of the need for better information on stand density effects on growth and yield, the Loblolly Pine Growth and Yield Research Cooperative at Virginia Tech installed a set of spacing trials. The study design is nonsystematic, allowing the spacing to be varied in two dimensions on a factorial basis with a constant number of plants per plot (Lin and Morse 1975). Thus the distance between rows and the distance between trees within rows are considered as two independent factors associated with each spacing treatment. This design results in factorial combinations of spacings occupying plots of unequal size grouped together to form one complete replication. Each measurement plot consists of 49 trees (7×7) with guard trees bordering each plot. Sixteen contiguous plots take up each replication. The within-row spacing factor and the between-row spacing factor have four levels: 4, 6, 8, and 12 feet (4 ft = 1.2 m). Measurement plots are separated by three guard rows. Each replicate covers approximately 2.25 acres (nearly 1 ha).

With this layout and choice of spacings, a range of initial densities from 303 trees per acre (748 per ha) to 2,722 trees per acre (6,723 per ha) can be examined. In addition, since the 6×8 and 4×12 foot spacings each allow 48 square feet per tree of growing space, rectangularity effects can be tested.

Three replications were established at each of four sites during 1983-84. The sites are in the upper Piedmont (Virginia), lower Piedmont (Virginia), upper Coastal Plain (North Carolina), and lower Coastal Plain (Virginia) physiographic regions. All four sites were hand planted with genetically improved 1-0 stock. Woody and herbaceous vegetation was controlled. First-year mortality was replaced with seedlings planted at the site.

Variables that have been measured annually include tree diameters (ground line diameter and then dbh) and total height. Beginning at age 2, three measures of crown width (within row, between rows, and maximum) have been collected. Height to the base of live crown and height to the maximum crown width have also been measured. (Additional information about the study can be found in Sharma et al. 2002.)

Modelling Response to Fertilizer Applications

Forest fertilization is an important silvicultural practice to improve stand productivity in loblolly pine plantations in the southeastern United States. Results from studies based on field trials demonstrate that nitrogen and/or phosphorus fertilization will produce significant growth response in midrotation loblolly pine plantations. We have carried out analyses of tree and stand response to fertilizer application in conjunction with the North Carolina Sate Forest Nutrition Cooperative, which is now jointly administered by North Carolina State University and Virginia Tech. Data from the Cooperative's Regionwide 13 study have been used to develop fertilizer response functions for stand-level (Amateis et al. 2000) and individual-tree level (Hynynen et al. 1998) models.

The Regionwide 13 study was established in 1984 and 1985 at locations across the southern United States. Stand ages at the time of plot establishment ranged from 11 to 14 years. At each study location, four levels of nitrogen (0, 112, 224, 336 kg N per ha) and three levels of phosphorus (9, 28, 56 kg P per ha) were examined using a factorial experimental design.

Amateis et al. (2000) developed response models for dominant height and basal area following midrotation nitrogen (N) and phosphorus (P) fertilization. Nonlinear regression models developed from the data predict total cumulative response as a function of the interaction of N and P application rates, drainage class of the site, stand conditions when fertilized, and time since fertilization. Stand variables that were found to be significant predictors of response included site index, age, basal area, number of surviving trees, and dominant height at fertilization. Dominant height response was significantly greater on poorly drained sites than on other sites. Basal area response to P was significantly less on poorly drained sites and significantly greater on well drained sites. These models can be coupled with baseline models for unfertilized stands to estimate volume response to midrotation fertilization.

Hynynen et al. (1998) predicted diameter and height growth in fertilized stands with a reference growth model multiplied by an equation predicting the relative growth response following fertilization. The temporal distribution of the growth response was modeled by the Weibull function. These equations for fertilizer growth response were developed to be compatible with individual-tree simulation models. Information about dose, nutrient elements, and time elapsed since fertilization are needed to predict the relative growth response following fertilization.

Modelling Response to Vegetation Control

Competing vegetation has a major impact on the development of commercial forests. (The book "Forest Vegetation Management for Conifer Production", edited by Walstad and Kuch, 1987, provides a comprehensive overview of treatment opportunities, silvicultural prescriptions, and methodologies for evaluating investments in forest vegetation management.) In the case of loblolly pine production in the US, the control of competing hardwood species is critical to successful plantation establishment and management, thus necessitating growth and yield models that incorporate effects of competing hardwoods on plantation production.

Burkhart and Sprinz (1984) developed a model to predict pine survival, growth and yield for unthinned loblolly pine plantations with varying levels of hardwood competition in the main canopy. Inputs for the model are number of loblolly pine trees per unit area planted, site index for loblolly pine, percent of hardwood basal area in the main canopy of the stand, and age(s) at which output is desired. From these inputs the model computes, by dbh classes, the number of trees surviving, basal area, and volumes per unit area.

The impact of competing hardwoods on height over age development, height over diameter relationships, individual tree volume equations, diameter distribution and survival relationships was examined. The principal impact of competing vegetation was to reduce survival and to shift the diameter distribution to the left.

The model, which was constructed using sample plot data from old-field and cutover-site plantations, was validated with independent data from a hardwood conversion/site preparation study. Overall, there was close agreement between the observed values and the model predictions.

Incorporating Genetic Effects

Tree improvement programs have been carried out in southern pines for more than 50 years (McKeand et al. 2003). Presently a wide variety of genetic stocks -- ranging from open-pollinated, to mass-control pollinated, to clonal material -- is available for planting. The potential for future gains in plantation productivity through genetic manipulation is large (Fox et al. 2007). Clonal forestry holds great promise for large gains in production. Vegetative propagation methods, such as somatic embryogenesis, to mass produce identical copies of selected individual trees with excellent genetic potential are now becoming feasible. Because of the rapidly changing nature of the genetic material being developed, we need growth and yield models that allow for a variety of genotypes as well as a range of silvicultural treatments.

Buford and Burkhart (1987) tested a series of hypotheses concerning stand dynamics and growth patterns in loblolly pine plantations of improved stock relative to plantations of unimproved stock. Results of these tests indicated that at the seed source and family levels: (1) the shape of the height-age curve is influenced by the site, but the level of the height-age curve is influenced by the seed sources or family; (2) at the seed source and family levels, the shape of the height-diameter relationship at a given age is influenced by the site and by the initial density; and (3) the level of the height-diameter relationship is affected by the seed source or family and is directly related to the dominant height of the seed source or family at that age. These results indicate that by specifying the height curve correctly, differences in development among seed sources and families on a given site can be modeled by altering the level only. Data from temporary plots in stands planted operationally with genetically improved stock were used to test for differences in stem quality and volume relationship as compared to comparable plots from unimproved plantations. Stem quality in the improved stands was not substantially different than in unimproved stands in the same region and of the same age range. There was no difference in stem taper or individual tree volume between improved and unimproved stock. Yield equations, based on the independent variables age, average height of dominants and codominants, and surviving number of trees, were fitted to these same plot data from operationally planted improved and unimproved stands. There were no significant differences in the yield equations, indicating that a single yield equation should suffice when the independent variable are correctly specified.

Although the results from Buford and Burkhart (1987) with a relatively low level of intensity of genetic selection (seed source and first generation open-pollinated) show that a simple adjustment in site index is sufficient for applying extant models for estimating stand productivity and structure, we do not know the impact of high levels of genetic selection, in particular planting stands of genetically identical individuals, on volume productivity, diameter distributions, mortality, maximum sized-density relationships, and other similar quantities.

SUMMARY

(1) Analytical methods and computing power generally do not limit development of reliable growth and yield models.
(2) Long-term empirical observations on stand development are expensive to obtain and often limit modelling efforts.
(3) Modelling is essential for integrating and synthesizing diverse information, identifying knowledge gaps, and making informed decisions.
(4) The questions being posed are more complex than in the past, thus further accentuating the need for comprehensive models of stand development.

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