APPROACHES TO MODEL MID-ROTATION TREATMENT EFFECTS IN LOBLOLLY PINE PLANTATIONS IN THE SOUTHEASTERN UNITED STATES

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Abstract—Loblolly pine (*Pinus taeda* L.) plantations are extensive in the Southeastern United States and represent a significant component of the forest products market in this region. For optimal stand-level management decisions, the growth response to any combination of mid-rotation silvicultural treatments like fertilization, thinning, or competing vegetation management needs to be accurately predicted over the long term. We present a review of the most common mid-rotation silvicultural treatments applied in loblolly pine plantations and provide a conceptual framework about their effects. Three theoretical expected types of responses are illustrated as a guide for better and more comprehensive modeling approach selection. Preliminary exploratory data analysis of remeasured plots from a mid-rotation treatment study established by the Plantation Management Research Cooperative at the University of Georgia indicates that basal area growth after thinning follow a Type I response and treatments such as thinning + fertilization or thinning + fertilization + vegetation control can follow either Type I or Type II responses. Finally, some thoughts are provided on how to improve the prediction accuracy of growth-and-yield models considering mid-rotation treatments.

INTRODUCTION

Throughout the Southern United States, pine plantations have made a significant expansion. Particularly, loblolly pine (*Pinus taeda* L.) plantations represent an essential sector of the forest products market in this region. At the same time, improvements in silvicultural practices and intensive management have shown a remarkable gain in productivity (Fox and others 2004). Mid-rotation silvicultural practices have shown important improvements in growth (Snowdon 2002). The most common silvicultural practices at mid-rotation are thinning, fertilization, and vegetation control. However, for optimal stand-level management decisions, the growth response after a specific silvicultural treatment, or combination of treatments, needs to be accurately predicted over the long term. Reliable estimates are critical for landowners to make informed management decisions or to evaluate investment opportunities.

Existing loblolly pine growth-and-yield equation systems have been extended with multiplicative or additive sub-models, also called "modifiers," at the stand level to represent the changes in growth due to individual silvicultural practices (Amateis 2000, Gyawali and Burkhart 2015, Pienaar 1997). Evidence of interactions between silvicultural treatments has been reported (Sword Sayer and others 2004), but little research exists that explicitly considers the interaction effect on the growth-and-yield equations system. Even fewer considerations have been given to the potential type of response that would be observed after a mid-rotation treatment is applied.

Consider the case of modeling the yield of a stand that received two or more mid-rotation silvicultural treatments. The simple addition of independently fitted modifiers (or the sequence of multiplications according to the case) does not guarantee an accurate prediction of the stand yield. A more elaborate procedure is needed in such a way that the resulting interactions of treatments are considered in growth-and-yield equation systems. Conventional statistical procedures could be used to estimate the effect of the interactions but require long-term field experimental data. To address this issue, the Plantation Management Research Cooperative (PMRC) at the University of Georgia has established and repeatedly measured several controlled loblolly pine mid-rotation silvicultural treatment (MRT) experiments across the Southeastern United States. Despite these efforts, not all the potential combinations of type and intensity of silvicultural treatments are available in controlled

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experiments. Additional information is required to improve the accuracy of the predictions, especially if they will be applied to sites different from those where the controlled experiments were established.

Alternatively, non-empirical growth models have been proven to perform successfully in explaining the stand-level growth responses to silvicultural treatments in loblolly pine and other species. These non-empirical models are known as process-based models. Simulation outputs of process-based models can be integrated as *a priori* knowledge with experimental data to improve the precision of growth predictions. Process-based models use well-established physiological models and only require environmental information, which is easily gathered and is available for the Southeastern United States. Prior research has shown that process-based models can model the productivity effects of mid-rotation treatments in loblolly pine plantations (Bryars and others 2013, Subedi and Fox 2016).

This paper reviews the most common mid-rotation silvicultural treatments applied in loblolly pine plantations and presents a conceptual framework about response types as a guide for model development. Also, preliminary results from a PMRC study are used to illustrate the expected nature of the responses in loblolly pine. Finally, some thoughts are provided on how to improve the accuracy in growth-and-yield predictions when several combinations of mid-rotation silvicultural treatments are present.

SILVICULTURAL TREATMENTS

Fertilization

Silvicultural practices serve to increase productivity in loblolly pine plantations. For example, mid-rotation fertilization with nitrogen (N; 150 to 200 pounds per acre) and phosphorous (P; 25 to 50 pounds per acre) on a majority of soils types throughout the Southeastern United States produces a large and consistent growth response in the volume of approximately 25 percent (Fox and others 2007). N and P fertilization with responses of approximately 55 cubic feet per acre per year have been shown to enhance the profitability of loblolly pine plantations (Fox and others 2007). Fertilization treatments increase nutrient availability at the tree level, and as a consequence, an increased leaf area index is expected, resulting in improved growth (Albaugh and others 2017).

Competition Control

At early ages, herbaceous and hardwood competition can adversely affect gains in growth (Jokela and others 2010). Early control of competing woody and herbaceous vegetation increases wood volume by 23 to 121 percent when evaluated at the age of 15 years (Miller and others 2003). At the tree level, competition reduces nutrient availability and increases competition for water, which influences radiation use efficiency.

Thinning

Thinning is another important silvicultural practice in loblolly pine plantations. There is evidence that thinning not only changes the structure of the stand (diameter distributions, and changes in spatial competition) but also alters the post-thinning height growth of dominant and codominant trees (Sharma and others 2006) and improves the stem quality of the residual stand. Thinning, in particular, has received considerable attention from researchers. Some studies of thinning effects have evaluated empirical approaches at the tree (Albaugh and others 2017, Soderbergh and Ledermann 2003) or stand level (Franklin and others 2009). Thinning is a way to modify the process of site resource allocation. In general, the primary objective of this treatment is to concentrate light, water, and nutrients on fewer and better trees that have the potential to survive over the entire rotation, ending up in a higher-value product.

MODELING MID-ROTATION TREATMENTS

The extra growth gained at the stand level (or plot level) is always referenced or measured with respect to the growth in the untreated stand (called the control plot or untreated plot) with similar site and stand structural attributes, including site index (SI), trees per acre (TPA), and basal area (BA). The treatments can be a single silvicultural practice or a combination of practices, and the expected response, which may also depend on several other stand characteristics such as age, could have a longer-term effect or a more temporary effect.

Long-term experimentation is the correct approach to infer about the growth drivers and is the only way to evaluate the magnitude of the response given specific treatments. However, these kinds of experiments are costly and time consuming to install and measure, and it is impossible to observe the response in all possible combinations of experimental factors across the Southern United States. Researchers conventionally have used experimental data to update growth-and-yield equations to be able to infer the expected response in a new location. This could involve either explicitly modeling the treatment effect into the growth-and-yield equations or modeling a response sub-model independently and using it as a modifier of the untreated growth-and-yield equations.

The explicit modeling of treatments has been done by incorporating silvicultural treatments into the growth-and-yield models as indicator variables (Fang and others 2001). This approach has two limitations: (1) it is difficult to separate the effects of different treatments at the stand level because each silvicultural treatment produces an enhanced growth response of different magnitude and duration, and (2) the positive responses in growth due to the implementation of a silvicultural treatment is attributed both to the improved treatment and a secondary effect of changes to stand stocking and/or structure that result from the improved treatment (Miller and Tarrant 1983).

The alternative approach consists of estimating a modifier equation. This method is used to adjust the typical or base pattern of growth of a plantation that has not received a given silvicultural treatment (also called the control case). Some researchers have found that the effect of the silvicultural treatment can be modeled using an additive modifier (Amateis 2000). In this case, the modifier is added to the base growth model. For example, the response of dominant height and basal area growth models for slash pine (*Pinus elliottii* Engelm.) in the Southern United States in response to bedding and herbicide treatment could be explained with additive modifiers (Pienaar and Rheney 1995). The volume responses to woody and herbaceous competition control at age 15 years in loblolly pine plantations were also found to be additive (Miller and others 2003).

Multiplicative modifiers have proven useful for growth-and-yield equations that consider thinning practices (Bailey and others 1985). For instance, a modifier can be incorporated into a procedure to evaluate the growth of a thinned plantation compared to a non-thinned plantation of the same age, SI, and TPA remaining in the thinned plantation immediately after thinning (Pienaar 1997). Today, this procedure, also known as the Index of Suppression, continues to be used in growth-and-yield models with thinning management practices. However, there are no recent studies that have validated this procedure for loblolly pine under more intensive management regimes.

Finally, updated growth-and-yield models are essential to project the long-term stand-level effects of silvicultural treatments, which help to support forest management decisions. This becomes even more important when one considers that field trials are challenging to replicate and cannot be installed due to their expensive and time-consuming nature (Weiskittel and others 2011).

Response-Type Models

A prior understanding of the potential types of stand growth response is important to guide the modeling strategy by defining appropriate modifier functional forms. Two response types to silvicultural treatments applied at the establishment or during early ages have been reported as Type I and Type II (Snowdon 2002). Here we define three possible types of basal area responses when silvicultural treatments are applied at mid-rotation (fig. 1). Type I responses are characterized by a temporary increase in growth rate after treatment compared with the untreated scenario or control, and an extra peak in growth is obtained. Thereafter, the treated stand growth gradually approaches back to the control. The yields of the treated and untreated stands follow a parallel trajectory (fig. 1A). This type of response is likely observed with practices that do not permanently change the site conditions, for example, additions of N fertilizer or weed control at mid-rotation.

Response Type II typically occurs when the treatment has a substantial and sustained effect on site properties. The resulting growth over time shows a parallel trajectory with the control growth after treatment. Consequently, a divergent trend in yield is observed when compared with the untreated stand condition (fig. 1B). Mid-rotation silvicultural practices that produce long-term changes in productivity are associated with Type II responses, such as an improvement in nutrient supply with phosphorous on soils with P deficiencies, irrigation, repeated N fertilization, or hardwood competition release.

Response Type III is characterized by a temporary increase in growth rate after treatment, but one that is not sustained over time. The initial gain in growth is followed by a decline in growth. Ultimately, yields are the same as the untreated scenario (fig. 1C). This type of response is likely observed when the treatments are applied on sites that are fully stocked and the intra-specific competition is increased due to the treatment.

Response Types I, II, and III could be combined with a thinning modifier. That is, if the silvicultural treatment is applied at the moment of thinning, then the theoretical response type may be observed on the growth curve for the remaining trees after thinning.

Case study—The Plantation Management Research Cooperative's Mid-Rotation Treatment study has 62 installations throughout the Southern United States established in non-thinned and thinned plantations. Five 0.75-acre treatment plots were established in each installation and trees in the 0.5-acre interior area were remeasured every 2 years since treatment was applied. One plot did not receive any treatment of thinning and four plots were assigned the following treatments: thinning only, thinning + fertilization (200N + 25P + additional nutrients based on foliar test), thinning + vegetation control, and thinning + fertilization + vegetation control.

Let us only consider the measurements from the non-thinned stands. For the sake of the example, we calculated the response as the difference in basal area between the treated plot and the control at each measurement age. We used the untreated plot as a control to compute the responses of the thinned plots. Therefore, we expected to see negative values for the response (fig. 2). A negative magnitude in

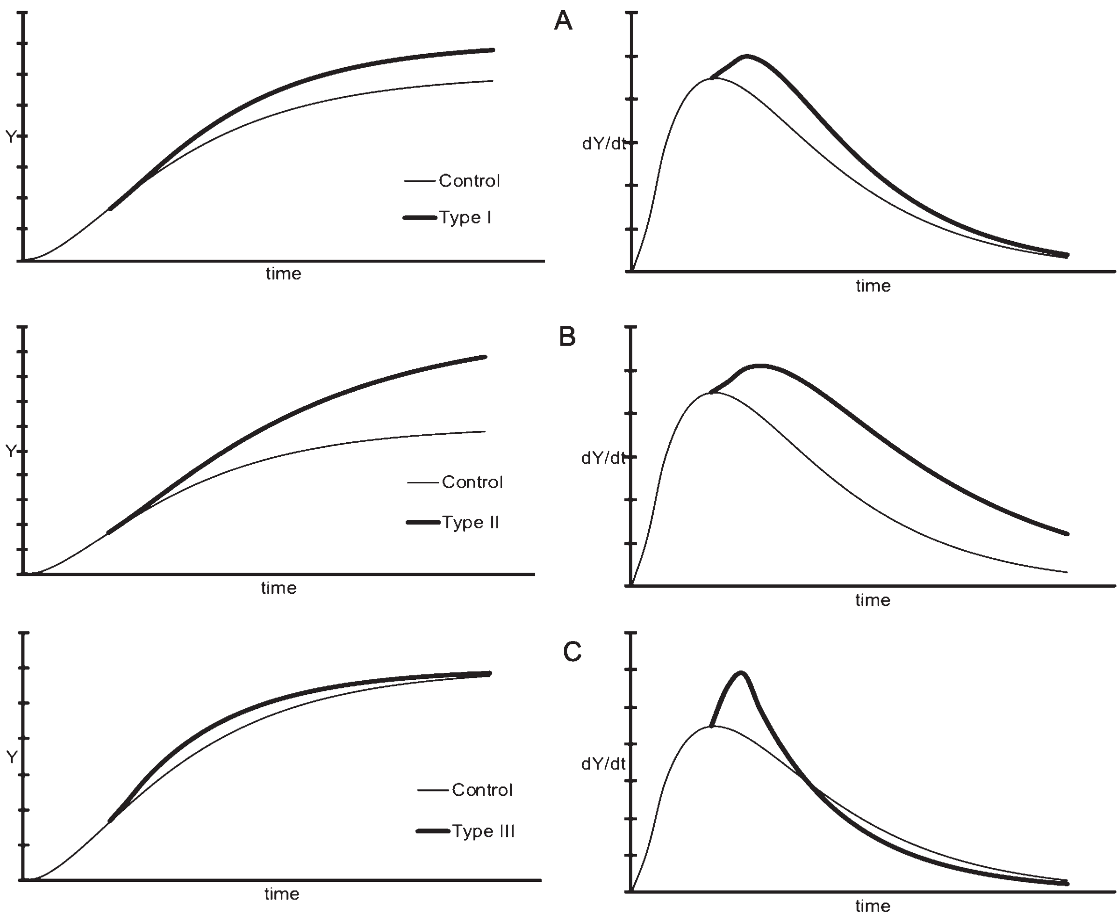

Figure 1—A theoretical pattern of responses to mid-rotation silvicultural treatments in yield and growth for the basal area of a loblolly pine plantation. (A) Type I response, (B) Type II response, and (C) Type III response.

response meant that the treatment reduced the stand characteristic that we were analyzing. This happened with stand-level basal area in the thinning treatment. Interestingly, in the three physiographic regions, the observed pattern over time resulted in a constant response, which implied that the thinned stands were following a Type I response.

The control plot for Thinning + Fertilization and Thinning + Fertilization + Vegetation Control was the Thinning only plot. We observed that some plots did not respond to combinations of treatments (fig. 3). Stands that are close to their productive potential have been shown to not respond to treatments (Zhao and others 2016). Plots with an increasing response over time indicate a Type II response. Here we only present the absolute response observed in the measured plots, but statistical modeling will be later developed, and the interactions between treatments will be tested with additional remeasurements.

Defining the expected response type is important for determining the modifier equation form. Depending on site and stand characteristics, it is likely that the interaction between treatments will produce a change in the response type. The next step in our research consists of testing a flexible modifier allowing it to account for the effects of physiographic region, thinning intensity, amount of vegetation competition at the thinning age. The modifier should also be able to represent either a Type I or Type II growth response.

Process-based Models

Some authors argue that process-based models per se are still limited concerning management and decision support because of their data and parameterization requirements (Franklin and others 2009, Mason and Dzierzon 2006). However, the process-based model 3-PG (Physiological Principles to Predict Growth) developed by Landsberg and Waring (1997) has proven to work very well in predicting long-term thinning responses in Scots pine (*Pinus sylvestris* L.) in Finland (Landsberg and others 2005); BGC-models (biogeochemical-mechanistic models) have been used with Norway spruce (*Picea abies* (L.) H. K.), and European beech (*Fagus sylvatica* L.) in central Europe (Petritsch and others 2007), and TRIPLEX (a hybrid monthly time-step model of forest growth, carbon, and

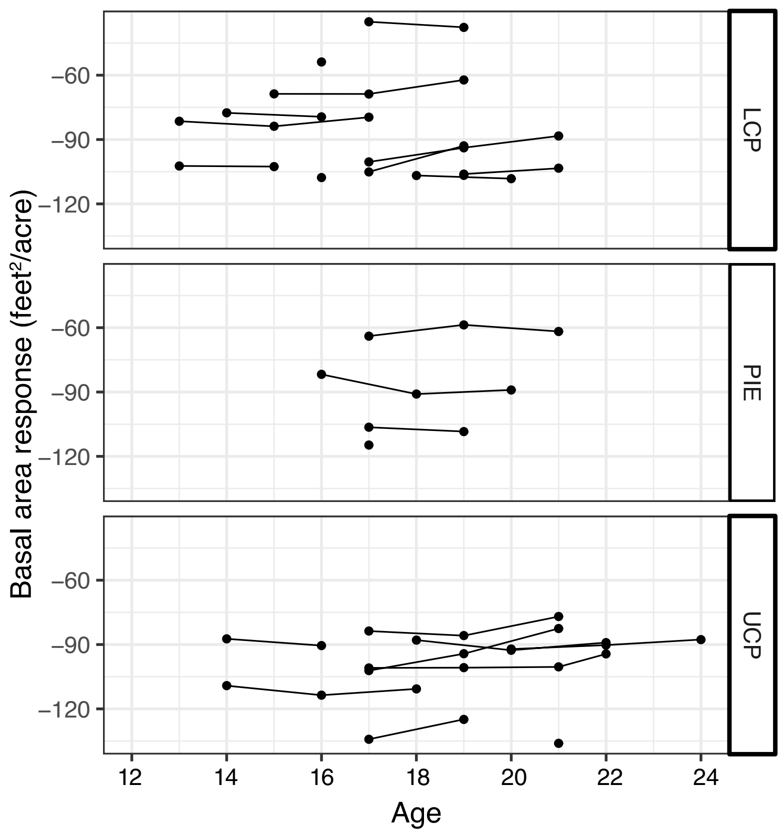

Figure 2—Basal area response to thinning over age for 25 installation plots of the PMRC MRT study grouped by physiographic region. LCP: Lower Coastal Plain, PIE: Piedmont, and UCP: Upper Coastal Plain. The response at each measurement was defined as the difference in basal area between the thinned plot and the unthinned control plot. The remeasurements of each plot are represented with dots connected by lines.

nitrogen dynamic) has been used for Jack pine (*Pinus banksiana* Lamb.) in Canada (Wang and others 2011).

The process-based model 3-PG (Landsberg and Waring 1997) is one of the simplest models readily available. The 3-PG model requires monthly climatic information and site soil characteristics to simulate stand growth. Outputs from this model include stem, foliage, and root biomass, stand volume, leaf area index, basal area, and mean diameters at each monthly step. The structural parameters needed to obtain predictions of biomass and volume in untreated stands throughout the Southeastern United States has been studied by Bryars and others (2013).

While 3-PG can be used to simulate thinning treatments (Landsberg and others 2005), it is not as versatile, in general, as the conventional growth-and-yield model equation systems. However, 3-PG could provide insight about the expected effect when several silvicultural treatments are combined. That is, once a calibrated 3-PG model is obtained for a particular site, it could be used to study the relative growth change under different silvicultural treatment intensities and timings. A reliable process-based model is valuable, especially to generate information about the expected effect of silvicultural treatments on sites where there are no existing trials, or to inform empirical models with prior information on interaction effects when few trial replications are available.

CONCLUSIONS

Since the silvicultural practices of vegetation competition control, fertilization, and thinning are known to have an impact on the future growth and yield of loblolly pine stands, it is important to understand how to incorporate these responses and their interactions into growth-and-yield models. The current loblolly pine models developed by the PMRC, as well as others in the literature, always consider the stand-level growth-and-yield models for the untreated conditions and use modifiers to adjust the projected growth as a response to individual silvicultural treatments. We illustrate hypothetical possible response types when mid-rotation treatments are present. Preliminary results from a PMRC MRT study show that the growth response of loblolly pine plots with mid-rotation treatments like Thinning + Fertilization or Thinning + Fertilization + Vegetation Control can be

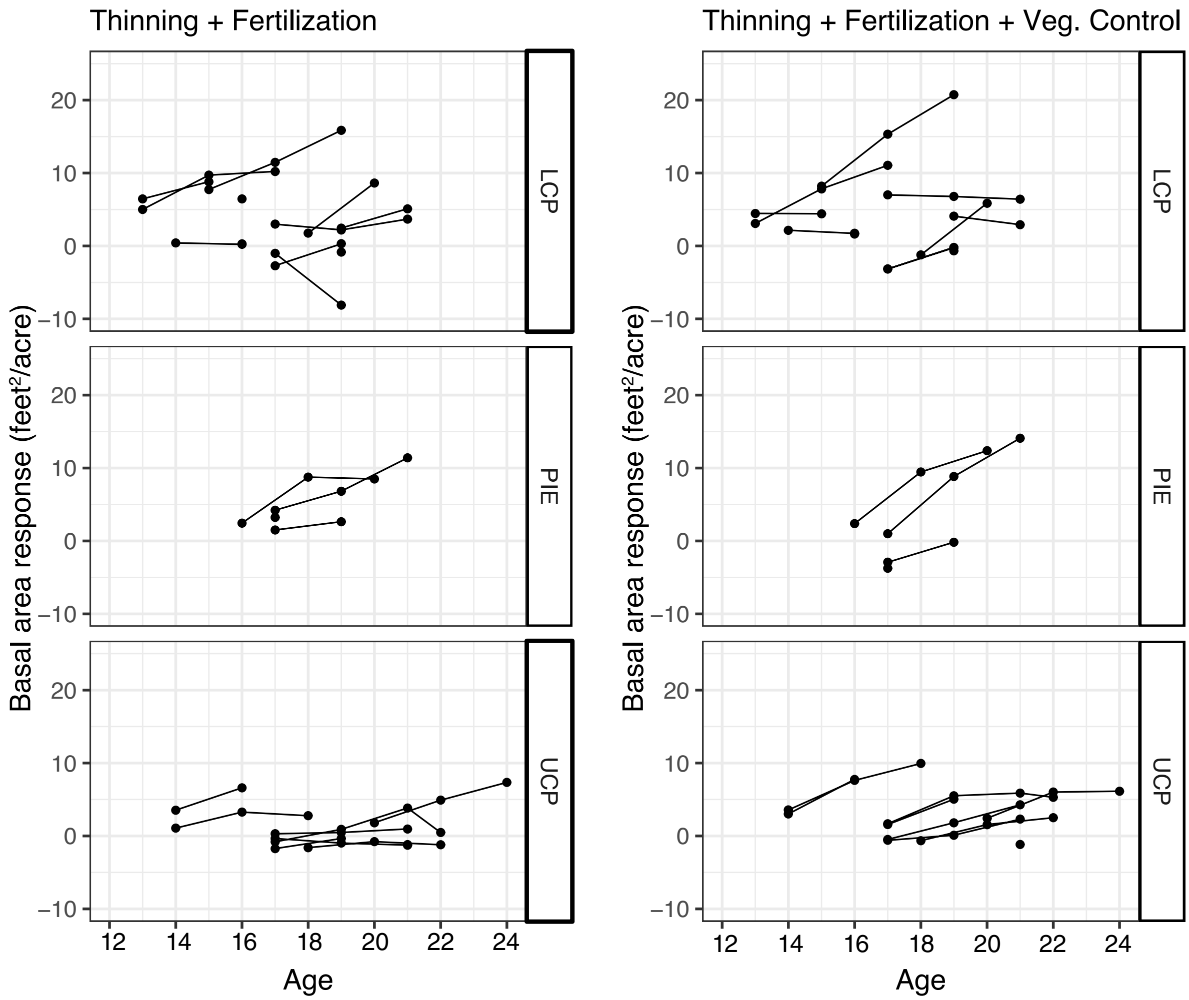

Figure 3—Basal area response to combinations of treatments over age: Thinning plus fertilization (left) and Thinning plus fertilization plus vegetation control (right). Installation plots of the PMRC MRT study grouped by physiographic region. LCP: Lower Coastal Plain, PIE: Piedmont, and UCP: Upper Coastal Plain. The response at each measurement was defined as the difference in basal area between the plots with combined treatments and the respective Thinning only control plot.

either Type I or Type II. Plots with Thinning only follow a Type I growth pattern exclusively. Process-based knowledge promises to be a useful source of information that can be incorporated as a piece of prior information in empirical models. Further research will evaluate the prediction accuracy of models combining experimental data and process-based information.

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LITERATURE CITED

Albaugh, T.J.; Fox, T.R.; Rubilar, R.A. [and others]. 2017. Post-thinning density and fertilization affect *Pinus taeda* stand and individual tree growth. Forest Ecology and Management. 396: 207–216.

Amateis, R.L. 2000. Modeling response to thinning in loblolly pine plantations. Southern Journal of Applied Forestry. 24(1): 17–22.

Bailey, R.L.; Borders, B.E.; Ware, K.D.; Jones, E.P. 1985. A compatible model relating slash pine plantation survival to density, age, site index, and type and intensity of thinning. Forest Science. 31(1): 180–189.

Bryars, C.; Maier, C.; Zhao, D.; [and others]. 2013. Fixed physiological parameters in the 3-PG model produced accurate estimates of loblolly pine growth on sites in different geographic regions. Forest Ecology and Management. 289: 501–514.

Fang, Z.; Bailey, R.L.; Shiver, B.D. 2001. A multivariate simultaneous prediction system for stand growth and yield with fixed and random effects. Forest Science. 47(4): 550–562.

Fox, T.; Allen, H.; Albaugh, T. 2007. Tree nutrition and forest fertilization of pine plantations in the southern United States. Southern Journal of Applied Forestry. 31(1): 5–11.

Fox, T.R.; Jokela, E.J.; Allen, H.L. 2004. The evolution of pine plantation silviculture in the southern United States. In: Rauscher, H.M.; Johnsen, K., eds. Southern forest science: past, present, and future. Gen. Tech. Rep. SRS-75. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station: 63-82.

Franklin, O.; Aoki, K.; Seidl, R. 2009. A generic model of thinning and stand density effects on forest growth, mortality and net increment. Annals of Forest Science. 66(815): 815–826.

Gyawali, N.; Burkhart, H.E. 2015. General response functions to silvicultural treatments in loblolly pine plantations. Canadian Journal of Forest Research. 45: 252–265.

Jokela, E.J.; Martin, T.A.; Vogel, J.G. 2010. Twenty-five years of intensive forest management with southern pines: important lessons learned. Journal of Forestry. 108: 338-347.

Landsberg, J.; Mäkelä, A.; Sievänen, R.; Kukkola, M. 2005. Analysis of biomass accumulation and stem size distributions over long periods in managed stands of *Pinus sylvestris* in Finland using the 3-PG model. Tree Physiology. 25(7): 781–792.

Landsberg, J.J.; Waring, R.H. 1997. A generalized model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. Forest Ecology and Management. 95(3): 209–228.

Mason, E.G.; Dzierzon, H. 2006. Applications of modeling to vegetation management. Canadian Journal of Forest Research. 36(10): 2505–2514.

Miller, J.H.; Zutter, B.R.; Zedaker, S.M.; [and others]. 2003. Growth and yield relative to competition for loblolly pine plantations to midrotation—a southeastern United States regional study. Southern Journal of Applied Forestry. 27(4): 237–252.

Miller, R.E.; Tarrant, R.F. 1983. Long-term growth response of Douglas-fir to ammonium nitrate fertilizer. Forest Science. 29(1): 127–137.

Petritsch, R.; Hasenauer, H.; Pietsch, S.A. 2007. Incorporating forest growth response to thinning within biome-BGC. Forest Ecology and Management. 242(2–3): 324–336.

Pienaar, L.V. 1997. An approximation of basal area growth after thinning based on growth in unthinned plantations. Forest Science. 25(2): 223–232.

Pienaar, L.V.; Rheney, J.W. 1995. Modeling stand growth and yield response to silvicultural treatments. Tech. Rep. 1995-2. Athens, GA: University of Georgia, Plantation Management Research Cooperative. 14 p.

Sharma, M.; Smit, M.; Burkhart, H.; Amateis, R.L. 2006. Modeling the impact of thinning on height development of dominant and codominant loblolly pine trees. Annals of Forest Science. 63: 349–354.

Snowdon, P. 2002. Modeling type 1 and type 2 growth responses in plantations after application of fertilizer or other silvicultural treatments. Forest Ecology and Management. 163: 229–244.

Soderbergh, I.; Ledermann, T. 2003. Algorithms for simulating thinning and harvesting in five European individual-tree growth simulators: a review. Computers and Electronics in Agriculture. 39(2): 115–140.

Subedi, S.; Fox, T.R. 2016. Modeling repeated fertilizer response and one-time midrotation fertilizer response in loblolly pine plantations using FR in the 3-PG process model. Forest Ecology and Management. 380: 90–99.

Sword Sayer, M.A.; Goelz, J.C.G.; Chambers, J.L. [and others]. 2004. Long-term trends in loblolly pine productivity and stand characteristics in response to thinning and fertilization in the West Gulf region. Forest Ecology and Management. 192(1): 71–96.

Wang, W.; Peng, C.; Zhang, S.Y. [and others]. 2011. Development of TRIPLEX-Management model for simulating the response of forest growth to pre-commercial thinning. Ecological Modelling. 222(14): 2249–2261.

Weiskittel, A.R.; Hann, D.W.; Kershaw, J.A.; Vanclay, J.K. 2011. Forest growth and yield modeling. West Sussex, UK: John Wiley and Sons, Ltd. 415 p.

Zhao, D.; Kane, M.; Teskey, R.; [and others]. 2016. Maximum response of loblolly pine plantations to silvicultural management in the southern United States. Forest Ecology and Management. 375: 105–111.