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New findings on loblolly pine plantations from long-term experimental field studies

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Abstract

Pine plantations in the southern US have been among the most intensively managed forests in the world. Their productivity has been enhanced by intensive silvicultural treatments over the past 60 years, and our knowledge about their treatment response has been expanded through long-term large-scale experimental studies. The analysis of nine long-term loblolly pine (*Pinus taeda* L.) field trials resulted in several new findings. For loblolly pine in the southern US, there exist maximum productivity and maximum response to silvicultural practices. The maximum response was inversely proportional to the base site quality. The maximum stand basal area (BA) and maximum stand density index (SDI) were redefined for individual stands. The average maximum stand BA and maximum SDI were 46.2 m^2 ha^{-1} and 1002 tph, respectively, and both showed significant variation (30.2– 61.7 m^2 ha^{-1} and 600–1410 tph, respectively). Stand aboveground net primary production (ANPP) generally increased with increasing site quality, due to increased stand foliage biomass in the early stage, and mainly due to increased growth efficiency in the late stages of stand development. More intensive silvicultural treatments increased foliage biomass, thus increased ANPP at early ages; thereafter silvicultural intensity did not affect foliage biomass, ANPP, and growth efficiency. The trend of early age increases in both foliage biomass and ANPP resulting from increased planting density did not hold true with stand development.

Keywords: pine plantation; maximum stand density index; maximum stand basal area; maximum response; intensive management

Introduction, scope and main objectives

Pine plantations in the southern US are among the most intensively management forests in the world. Over the past 60 years, the productivity of pine plantations has tripled, due to intensive silvicultural treatment including site preparation, competition control, fertilization, and the development of genetically improved seedling stock (Fox et al. 2007a, Jokela et al. 2010, Martin and Jokela 2004, Zhao et al. 2009a,2009b, 2011). As more and more herbicide and fertilizers are being used in pine plantations, forestland owners and managers may ask: how much more productivity can we increase by additional silvicultural treatments, and is there maximum response?

In forestry, maximum stand basal area (BA) and maximum stand density index (SDI) are often used to express stand carrying capacity or to calculate the relative stand density. However, their definitions are inconsistent in literature. The previous definitions are associated with an upper boundary or asymptote of BA observations of a group of stands, without considering development

differences between individual stands. The second question is: can we define maximum stand BA and maximum SDI for individual stands?

Numerous studies reported a strong positive relationship between foliage biomass or leaf area index (LAI) and productivity in young stands. However, stand foliage biomass or LAI in mid- or late-rotation pine plantations are relatively stable or decreasing. Results for young plantations are not good predictors for fertilizers or herbicide treatment responses at mid- or late-rotation. The third question is: what are the relationships among foliage biomass, ANPP, and growth efficiency in mid-rotation plantations?

In this presentation, these three questions will be answered by analyzing long-term growth monitoring data from nine loblolly pine field studies across the southern United States.

Methodology/approach

Six long-term field studies were used to evaluate growth response to silvicultural treatments, in terms of site index (SI) response. SI response (ΔSI) was defined as the difference of the expressed SI of intensively managed plots minus the base SI for a given planting density within the same installations. Then the SI responses to intensive treatments were regressed to the base SI using linear quantile regression: $\Delta SI = \beta_0^{(\tau)} + \beta_1^{(\tau)} SI_{base} + \varepsilon^{(\tau)}$.

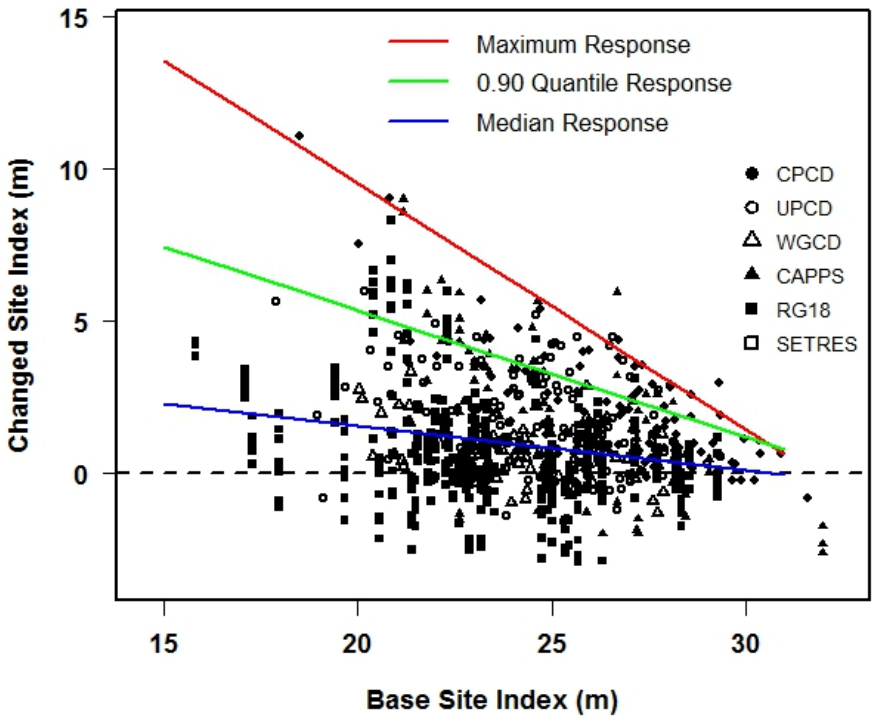

Fig. 1: A scatterplot of 850 observations of change in site index (ΔSI) and the base site index (SI_{base}) with 0.99, 0.90, and 0.50 regression quantile estimates for the model $\Delta SI = \beta_0^{(\tau)} + \beta_1^{(\tau)} SI_{base}$ (Zhao et al. 2016).

For individual stands, the development of BA and SDI followed similar patterns: increase to a maximal then decrease or increase to an asymptote. Therefore, the maximum BA could be defined as the maximal or asymptotic BA of individual stands. The maximum SDI could be defined in the same way.

The conditions for individual stands to achieve their maximum BA and maximum SDI were deduced from the mathematical relationships among stand BA, SDI, the number of trees per hectare (N), and quadratic mean diameter (Dq) trajectories. Then these conditions were verified using data from six long-term loblolly pine research studies. The observed maximum stand BA and the ages at which stands attained their maximum BA were shown in Fig. 2. Effects of silvicultural intensity, planting density, site quality, and their interactions on the magnitude and timing of maximum stand BA were analyzed with regression analysis.

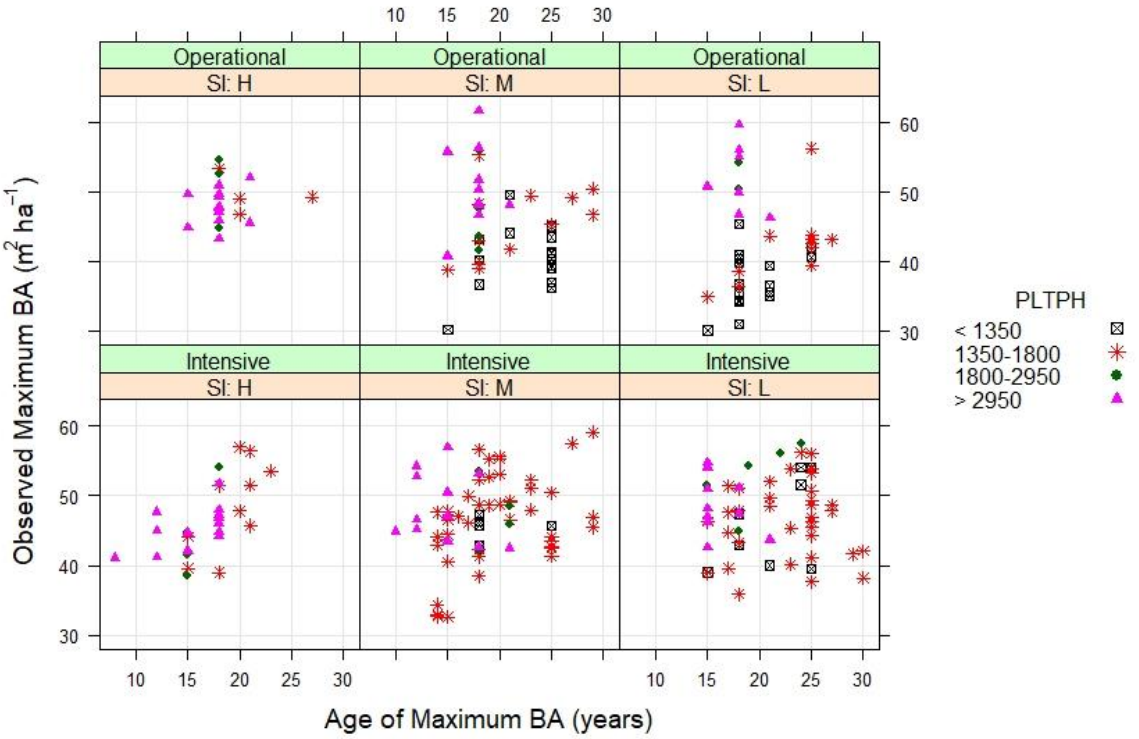

Fig.2: The magnitude and timing of maximum stand BA by silvicultural intensity (operational vs. intensive), site quality class (H: high-quality; M: mid-quality; L: low-quality), and planting density (PLTPH) (Zhao et al. 2020a).

The relationship between ANPP and foliage biomass in mid-rotation loblolly pine plantations was investigated using data from 15 non-thinned installations of two silviculture and density studies. Each installation had 12 plots, a combination of 2 levels of silvicultural intensity (operational and intensive) and 6 levels of planting density (741, 1483, 2224, 2965, 3706, 4448 TPH). Plots were measured from 2 to 21 years. Stand aboveground net primary production (ANPP) and foliage biomass (FB) were calculated for each plot at measurement points (Zhao et al. 2020b). The rules of planting density, silvicultural intensity, and site quality on stand ANPP and growth efficiency were investigated using an analysis of covariance (ANCOVA) with linear mixed-effects modeling approach.

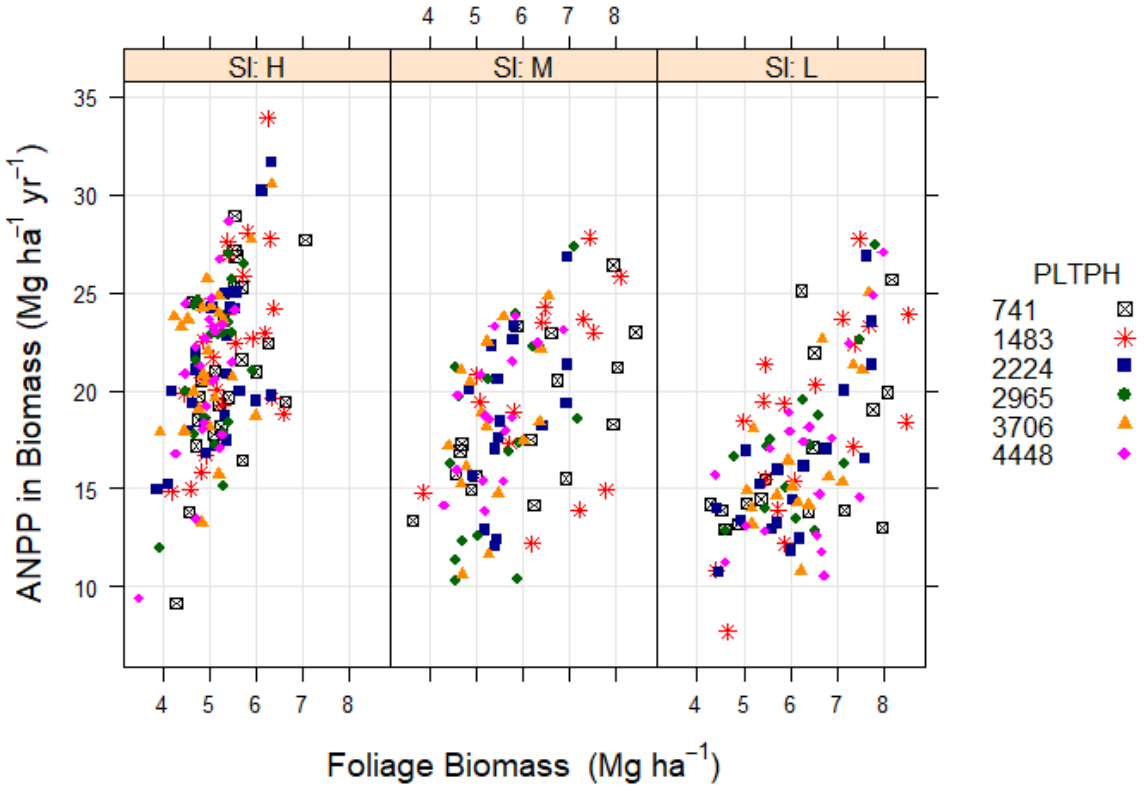

Fig. 3: Relationship between stand aboveground net primary production (ANPP) and foliage biomass when stand age ≥ 15 years by planting density (PLTPH) and site quality class ((H: high-quality; M: mid-quality; L: low-quality) (Zhao et al. 2020b).

Results

26% of the 850 plots that received increased silvicultural inputs did not respond to treatment or even had a negative response (Fig. 1). The potential SI increase due to intensive silviculture was inversely proportional to the base SI, indicating greater response on lower quality sites. The maximum response was defined by the 0.99 conditional quantile given the base SI: $\Delta SI = 25.74 - 0.81 SI_{base}$. There is a maximum SI for loblolly pine in the southern US that is around 31 m at base age 25 years.

Based on the mathematical relationships among stand BA-, SDI-, N- and Dq-age trajectories, it is derived that stands would achieve their maximum BA only after reaching their maximum SDI. The observed difference between the age to achieve maximum BA and the age to maximum SDI ranged from 0 to 12 years with a mean of 1.5 year, which confirmed again that stands would achieve maximum BA when or mostly after achieving their maximum SDI.

The observed maximum BA ranged from 30.2 – 61.7 $m^2 ha^{-1}$ with an average of 46.2 $m^2 ha^{-1}$; the ages to attain maximum BA ranged 8 – 30 years with a mean 20 years (Fig. 2). Maximum SDI also showed significant variation (600 – 1410 TPH) with an average 1002 TPH. Stands that achieved higher maximum SDI would achieve higher maximum BA. With information of site quality, initial density and silvicultural treatments, the magnitude and timing of maximum BA could be estimated (Zhao et al. 2020a).

ANPP of operational stands increased over age 4-18 years, thereafter, decreased. ANPP of intensive stands flattened before age 12 on high-quality sites or increased until age 12 then decreased on low-quality sites. In general, ANPP increased with increasing site quality. ANPP increased with increasing planting density at early ages; after age 12 this trend did not hold true.

Regardless of initial density, silviculture and site quality, the ANPP-FB relationship in loblolly pine plantations was very strong before age 8 years, moderately strong over ages 8-15 years, and very weak after age 15 years. Further analysis indicated that the ANPP-FB relationship after age 15 years was significantly affected by site quality, but not by silvicultural intensity or planting density (Fig. 3). Loblolly pine plantations on higher quality sites had higher growth efficiency.

Discussion

The positive responses to silvicultural treatments observed on many sites are consistent with results from past research on the positive impacts of competition control (Miller et al. 2003) and fertilization (Fox et al. 2007b) on loblolly pine productivity. We found the growth response to silvicultural management decreased as the base site index increased. Our analysis also found a lack of a growth response, or a decrease in growth, after silvicultural treatments were applied to some plots across the range of the base site index. The lack of a marked positive response may be because the treatment did not provide limiting resources (e.g., fertilization on a site where nutrients are not limiting productivity or vegetation control on a site with no or very low competition vegetation) or the trees are limited by some resources other than that provided by the treatment (e.g., fertilization on a site where soil moisture strongly limits growth).

In most previous studies, the maximum stand BA was used in two different ways: the maximum stand BA at any age or the greatest maximum stand BA (Yang and Burkhart 2017, 2018). Our new definition of maximum stand BA from the aspect of stand dynamics can not only provide an actual (rather than potential) value of the greatest maximum stand BA for a group of stands or region, but also, more importantly, provide the magnitude and timing of maximum BA and maximum SDI in individual stands so that we can analyze how site and stand conditions influence them.

Loblolly pine productivity is a function of foliage quantity (Vose and Allen 1988, Albaugh et al. 1998, Jokela and Martin 2000). The changed growth efficiency with stand development or caused by silvicultural practices or natural site variability should also be taken into consideration for describing the relationship. After age 15, for example, operationally managed loblolly pine stands on low-quality sites maintained considerably more foliage biomass but still had lower ANPP than intensively managed stands on high-quality sites, because of lower growth efficiency on low-quality sites. More intensive treatments increased foliage biomass, thus increased ANPP at early ages (i.e., before age 10), thereafter did not affect foliage biomass, ANPP, and growth efficiency. This early “push” effect, especially on higher quality sites did not guarantee higher yields, because site quality and most silvicultural treatments that increase early growth of pine stands are associated with increased mortality rates.

Conclusions/ wider implications of findings

For loblolly pine plantations in the southern US, there are a maximum SI and a maximum response to silvicultural treatments. Maximum SI and maximum response mean that the productivity

potential and thus carbon sequestration potential of loblolly pine plantations may be finite and can be defined. A large potential response to silviculture on poor quality sites and a small response on high quality sites suggest we can optimize silvicultural prescriptions for specific sites (precision silviculture).

New maximum stand BA and maximum SDI are defined for individual stands. Stands would achieve their maximum BA only after reaching their maximum SDI, which has been theoretically proved and empirically verified. Although both maximum stand BA and SDI showed significant variation, their magnitude & timing could be estimated with the information of site quality, initial density, and silviculture. The maximum stand BA and maximum SDI identified from the aspect of individual stand development could provide a realized carrying capacity for individual stands, which are critical for developing site-specific (even stand-specific) management regimes such as thinning intensity and timing.

Loblolly pine ANPP increased with increasing site quality, due to increased foliage biomass at early ages, and thereafter due primarily to an increase in growth efficiency. More intensive treatments increased foliage biomass and thus increased ANPP at early ages. Thereafter more intensive treatments did not alter stand foliage quantity, ANPP and growth efficiency. Both foliage biomass and ANPP increased with increasing planting density at early ages, and thereafter density-induced differences in foliage biomass, ANPP, and growth efficiency were less pronounced.

As pine plantation management is shifting from short-rotation production of fiber back to long(er)-rotation management for high-value solid wood products, intensive silvicultural practices currently implemented in young stands need to be modified and optimized. The new findings of long-term responses to intensive silvicultural treatments and responses to mid- or late-rotation treatments help us develop site-specific management regimes.

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References

Albaugh TJ, Allen HL, Dougherty PM, Kress LW, King JS. 1998. Leaf area and above- and belowground growth response of loblolly pine to nutrient and water additions. Forest Science, 44: 317-328.

Fox TR, Jokela EJ, Allen HL. 2007a. The development of pine plantation silviculture in the southern United States. Journal of forestry, 105: 337-347.

Fox TR, Allen HL, Albaugh TJ, Rubilar R, Carlson CA. 2007b. Tree nutrition and forest fertilization of the pine plantations in the southern United States. Southern Journal of Applied Forestry, 31: 5-11.

Jokela EJ, Martin TA. 2000. Effects of ontogeny and soil nutrient supply on production, allocation, and leaf area efficiency in loblolly and slash pine stands. Canadian Journal of Forest Research, 30(10): 1511-1524.

Jokela EJ, Martin TA, Vogel JG. 2010. Twenty-five years of intensive forest management with southern pines: important lessons learned. Journal of Forestry 108(7): 338-347.

Main TA, Jokela EJ. 2004. Stand development and production dynamics of loblolly pine under a range of cultural treatments in north-central Florida USA. Forest Ecology and Management, 192(1): 39-58.

Miller JH, Zutter BR, Zedaker SM, Edwards MB, Newbold RA. 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.

Vose JM, Allen HA. 1988. Leaf area, stemwood growth, and nutrient relationships in loblolly pine. Forest Science, 34(3): 547-563.

Yang SI, Burkhart HE. 2017. Estimation of carrying capacity in loblolly pine (*Pinus taeda* L.). Forest Ecology and Management, 385: 167-176.

Yang SI, Burkhart HE. 2018. Application of height-based and diameter-based relative spacing for estimation of stand basal area. Forest Science, 64(1): 28-32.

Zhao D, Kane M, Borders BE, Harrison M. Rheney J. 2009a. Site preparation and competing vegetation control affect loblolly pine long-term productivity in the southern Piedmont/Upper Coastal Plain of the United States. Annals of Forest Science, 66: 75.

Zhao D, Kane M, Borders BE, Harrison M. 2009b. Long-term effects of site preparation treatments, complete competition control, and repeated fertilization on growth of slash pine plantations in the flatwoods of the southeastern United States. Forest Science, 55: 403-410.

Zhao D, Kane M, Teskey R, Fox TR, Albaugh TJ, Allen HL, Rubilar R. 2016. Maximum response of loblolly pine plantations to silvicultural management in the southern United States. Forest Ecology and Management, 375: 105-111.

Zhao D, Bullock BP, Montes CR, Wang M, Greene D, Sutter L. 2019. Loblolly pine outperforms slash pine in the southeastern United States – a long-term experimental comparison study. Forest Ecology and Management, 450: 117532.

Zhao D, Bullock BP, Montes CR, Wang M. 2020a. Rethinking maximum stand basal area and maximum SDI from the aspect of stand dynamics. Forest Ecology and Management, 475: 118462.

Zhao D, Bullock BP, Montes CR, Wang M, Westfall J, Coulston, JW. 2020b. Long-term dynamics of loblolly pine crown structure and aboveground net primary production as affected by site quality, planting density and cultural intensity. Forest Ecology and Management, 472: 118259.