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Maximum response of loblolly pine plantations to silvicultural management in the southern United States

Dehai Zhao [a,*], Michael Kane [a], Robert Teskey [a], Thomas R. Fox [b], Timothy J. Albaugh [b], H. Lee Allen [c], Rafael Rubilar [d]

[a] Warnell School of Forestry and Natural Resources, University of Georgia, Athens, GA 30602, USA
[b] Department of Forest Resources and Environmental Conservation, Virginia Polytechnic and State University, Blacksburg, VA 24061, USA
[c] Department of Forestry and Environmental Resources, North Carolina State University, Raleigh, NC 27695, USA
[d] Departamento de Silvicultura, Facultad de Ciencias Forestales, Universidad de Concepción, Concepción, Chile

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ABSTRACT

Pine plantations in the southern US are among the most intensively managed forests in the world and their productivity has tripled over natural pine forests through application of intensive pine plantation establishment and management practices. As we are trying to increase carbon (C) sequestration through further enhancing pine plantation productivity by refinement of silvicultural regimes, whether a maximum productivity or the maximum potential C sequestration exists remains unclear. Our analysis of six long-term field trials indicated that a maximum productivity and a maximum response to silvicultural practices for loblolly pine (*Pinus taeda* L.) exist across the species geographic range in the southern US. The maximum response was inversely proportional to the base site quality, and silvicultural treatments never increased productivity above that maximum. Further analysis of loblolly pine culture and density studies demonstrated that the effects of planting density and cultural treatment intensity on biomass production strongly interacted with site quality in that lower quality sites responded more to silvicultural intensity than higher quality sites. The results highlight that we can optimize silvicultural prescriptions for specific sites by changing silvicultural intensity depending on the site quality.

1. Introduction

In the southern US, there are 87 million hectares of forestland including about 10 million hectares of naturally regenerated pine forests and 14 million hectares of pine plantations. These forests provide a wide range of environmental, social and economic values and services. They not only produce about 16% of global industrial wood, which is more than any other country (Prestemon and Abt, 2002), but also contain 36% of the sequestered forest carbon (C) in the conterminous US (Turner et al., 1995). Pine forests in the region annually sequester 76 Tg C, equivalent to 13% of regional greenhouse gas emissions (Johnsen et al., 2001). Over the past 50 years, the productivity of pine plantations has tripled (Fox et al., 2007b; Jokela et al., 2010) over natural pine forests due to silvicultural manipulations including site preparation, weeding, and fertilization, and the development of genetically improved seedling stock (Martin and Jokela, 2004; Zhao et al., 2009a,b, 2011). Pine plantations in the southern US have been among the most intensively managed forests in the world. Now, researchers and forest landowners are trying to increase C sequestration by changing silvicultural practices to further enhance productivity of pine plantations. To determine the maximum potential carbon sequestration possible in these forests and to increase the productivity, profitability and sustainability of plantation silviculture requires answers to two fundamental questions: (a) How much more can forest productivity be increased by additional silvicultural treatments in the southern US? (b) Does the growth response to increased silvicultural intensity vary across the region?

A substantial amount of research has focused on increasing productivity in loblolly pine plantations, and growth and yield responses to common silvicultural inputs have been documented (Borders and Bailey, 2001; Nilsson and Allen, 2003; Albaugh et al., 2004; Jokela et al., 2004; Fox et al., 2007a, 2007b; Zhao et al., 2008, 2009a, 2009b, 2011). However, the maximum achievable productivity has not been reported, with the exception of Farnum et al. (1983) who used a theoretical model to estimate a maximum potential productivity of loblolly pine on high quality sites in the Lower Coastal Plain of North Carolina to be 30 Mg ha^{-1} y^{-1}.

* Corresponding author.
E-mail address: zhaod@uga.edu (D. Zhao).

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The overall response to silvicultural treatments across sites has been commonly reported in literature. However, this approach disregards the response variation among different locations and soils. Site-specific response information can be very informative, but not often reported. Albaugh et al. (2015) observed that pine response to fertilization was influenced by soil drainage and texture, and only about 36% of sites had a significant treatment effect. In a long-term (26 year) study, Zhao et al. (2009b) found that complete competition control and repeated fertilization consistently and significantly increased slash pine productivity, with greater responses occurring on Spodosols than non-Spodosols. They also found that some site preparation treatments had significant effects only on non-Spodosols, while other treatments had no significant effect in plantations on either soil group. These findings suggested that there were complex responses of pines to silvicultural treatments, which appeared to be determined by resource limitations and site-specific conditions.

Various growth measures such as average height, average dbh, stand basal area, stand volume, and biomass have been used to describe the response to silvicultural treatments. However, different response patterns have been obtained, depending on which measure was used (Zhao et al., 2008, 2009b). Many important stand characteristics, such as volume and biomass, are related to stand age, stocking density and site quality. It is oftentimes hard to use volume or biomass to compare the results from different studies which have different ages and stocking. To avoid this problem, the change in site index can be used as the measure of response to management regimes. Site index is determined from the height of dominant and co-dominant trees in a stand at a base age, thus is little affected by stand density (Clutter et al., 1983). It is also determined for a fixed age, so that variable is also eliminated, leaving only site quality. Site index serves as an indicator of site quality and is a key driver in most growth and yield models. It is also a species-specific measure of actual or potential forest productivity (usually for even-aged stands). So a change in site index of a stand can indicate the change in productivity caused by different silvicultural practices.

The objective of this study was to address two fundamental questions mentioned above, using a meta-analysis of six long-term field studies designed to obtain growth data for loblolly pine plantations managed at different levels of silvicultural intensity. Our hypotheses were that: (1) there is a maximum productivity of loblolly pine plantations in the southern US; (2) there is a maximum response to silvicultural treatments and the response is inversely related to site quality; and (3) there are significant interactions among silvicultural intensity, planting density and site quality. The first two hypotheses were tested by the change in site index using a linear quantile regression approach. The third one was tested by the change in biomass production using a mixed-effects modeling approach.

2. Materials and methods

2.1. Data

The data came from six field studies that provided long-term growth data under carefully controlled conditions for loblolly pine plantations managed at varying levels of silvicultural intensity which are described below and summarized in Table 1.

(1) The Plantation Management Research Cooperative (PMRC) Coastal Plain culture/density study (CPCD), which was established in 1995/1996 at 17 locations in the Lower Coastal Plain of Georgia (GA), Florida (FL) and South Carolina (SC), across five soil groups (Zhao et al., 2010). At each location, there were six levels of planting densities (741, 1485, 2224, 2965, 3706 and 4448 trees ha^{-1}) and two levels of cultural treatment (intensive and operational). A split-plot design with one replication was used in which cultural intensities were randomly assigned to main plots and within a cultural intensity level the planting densities were randomly assigned subplots. In the CPCD study, the operational treatment consisted of bedding in the spring followed by a fall banded chemical site preparation. The intensive cultural treatment included bedding in the spring followed by a fall broadcast chemical site preparation, tip moth control through the first two growing seasons and repeated herbicide applications to achieve complete vegetation control throughout the rotation. At planting, 561 kg ha^{-1} of 10-10-10 fertilizer was applied on all plots. The operation treatment plots were fertilized with the equivalent of 224 kg N ha^{-1} and 28 kg P ha^{-1} before 8th and 12th growing seasons. The intensive cultural treatment plots also received 673 kg ha^{-1} of 10-10-10 plus micronutrients and 131 kg ha^{-1} of NH_4NO_3 in the spring of 3rd growing season, 131 kg ha^{-1} NH_4NO_3 in the spring of 4th growing season, 336 kg ha^{-1} NH_4NO_3 in the spring of 6th growing season, and 224 kg N ha^{-1} and 28 kg P ha^{-1} in the spring of 8th, 10th, 12th and 14th growing seasons.

(2) The PMRC Upper Coastal Plain and Piedmont culture/density study (UPCD) which was established in 1997/1998 at 23 locations in the Upper Coastal Plain and Piedmont regions of GA, FL, SC, Alabama (AL) and Mississippi (MS), across seven broad soil classes (Zhao et al., 2010). Planting density treatments and experimental design were identical and the two cultural treatments somewhat different from that of the CPCD study. In the UPCD study, all tillage treatments included in site preparation were carried out on all treatment plots. Both the operational and intensive treatments included a broadcast chemical site preparation. The operational treatment included a first-year banded weed control. The intensive cultural treatment included additional herbicide application for complete competing vegetation control throughout the rotation. The same level of fertilization as in the CPCD study was applied in the operational and intensive treatments.

(3) The PMRC Western Gulf culture/density study (WGCD) was established in 2001/2002/2003 at 18 locations in Arkansas (AR), Louisiana (LA), MS and Texas (TX), across four soil types. Each installation consisted of 10 plots, each plot representing a unique combination of five levels of planting density (494, 1112, 1730, 2347, 2963 trees ha^{-1}) and two levels of cultural intensity (operational vs intensive). The operational regime included soil group specific, mechanical site preparation, tip moth control during the first two growing seasons, and competition control and fertilization during the first growing season. The intensive regime included operational treatments plus additional competition control and fertilization treatments as described in Kane et al. (2015).

(4) The Consortium for Accelerated Pine Production Studies (CAPPS) was initiated in 1987 with 6 installations in GA and monitored through age 25 years (Borders and Bailey, 2001). Each installation had six blocks in which four treatment plots were assigned one of four treatments: (1) herbicide (controlling competing woody and herbaceous vegetation using herbicides through the rotation); (2) fertilization (280 kg ha^{-1} diammonium phosphate plus 112 kg ha^{-1} potassium chloride applied in the spring followed by 56 kg ha^{-1} diammonium phosphate applied in midsummer in the first and second year after planting, and