Plantation Management Research Cooperative
Warnell School of Forestry & Natural Resources
UNIVERSITY OF GEORGIA

Some new findings on loblolly pine plantations from long-term large-scale experimental studies

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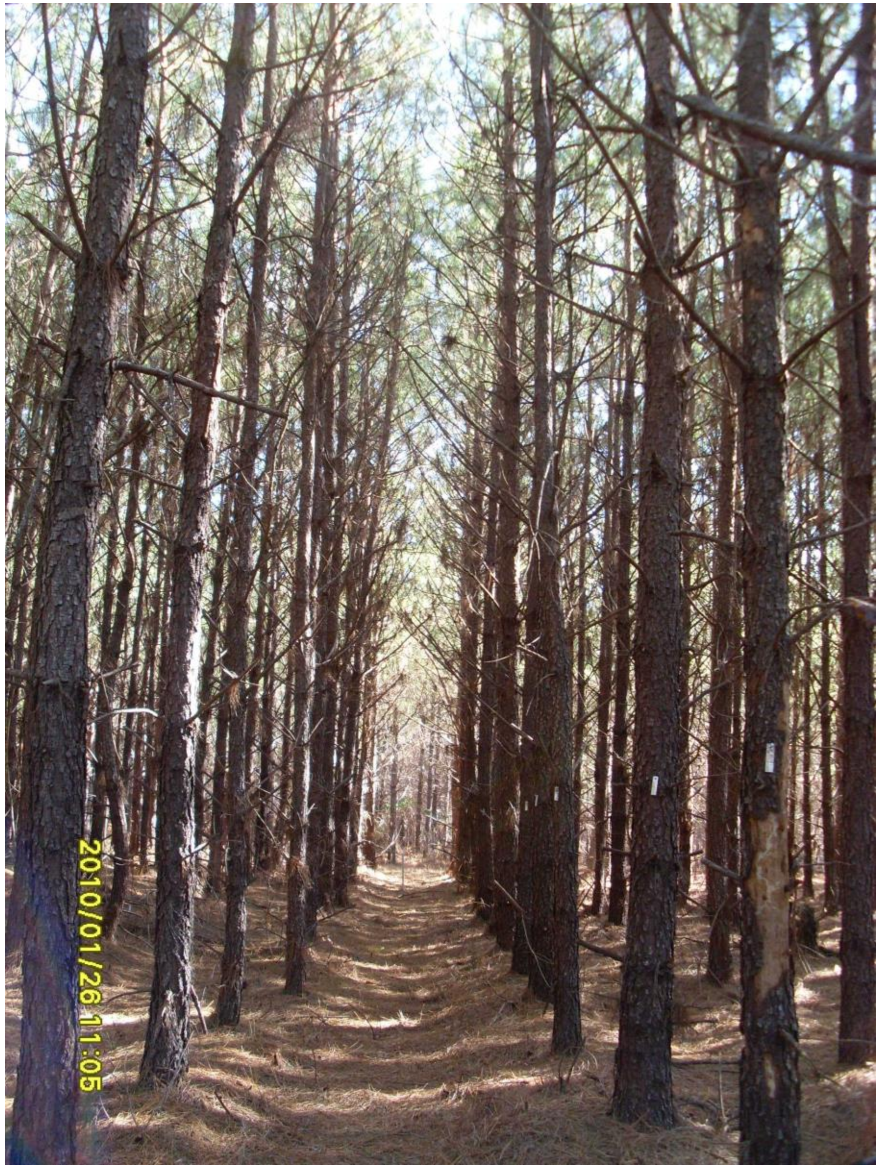
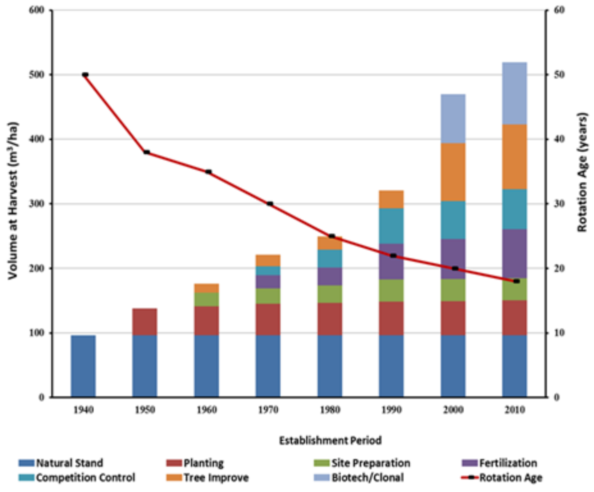
Highlights

- Maximum response to silviculture
- Maximum stand basal area (BA_{MAX}) & maximum stand density index (SDI_{MAX})
- Stand foliage biomass, aboveground net primary production (ANPP), & growth efficiency during mid-rotation stage



Introduction

- Southern pine plantations are among the most intensively managed 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, and fertilization
- **Question I:** How big potential of site productivity can we increase?
  - Is there maximum response to silvicultural treatment in the southern US?
  - How the responses change in different sites?



Redrawn from Fox et al. (2007) and Jokela et al. (2010)

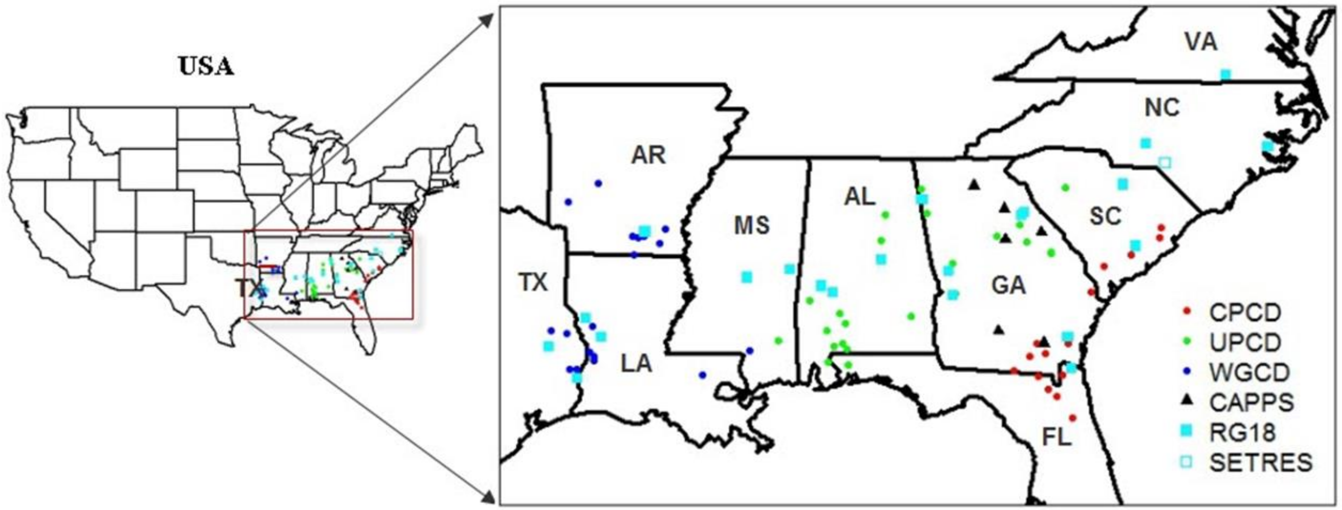
Introduction

- SDI_{MAX} and BA_{MAX} are often used to express stand carrying capacity or to calculate relative stand density – *SDI/SDI_{MAX}* or *BA/BA_{MAX}*
- SDI_{MAX} of 1100 TPH (450 TPA) for loblolly pine, not necessarily typical
  - Observed SDI_{MAX}: 600 – 1410 TPH
- %SDI used to set thinning intensity and timing, which SDI_{MAX} should be used?
  - 1100 TPH or ***stand-specific SDI_{MAX}***
- BA_{MAX}: the highest stand BA, asymptotic BA, or ***stand-specific BA_{MAX}***
- **Question II:** How to define and estimate BA_{MAX} & SDI_{MAX} for individual stands?

Introduction

- Numerous studies reported a strong positive relationship between foliage biomass or leaf area index (LAI) and productivity <u>in young stands</u>
  - Most silvicultural treatments that increase growth of pine stands are associated with increased foliage biomass
- As stands develop, however, foliage biomass or LAI become relatively stable
  - Thus, the early-age strong positive relationship might no longer hold true
- **Question III:** What are the relationships among foliage quantity, ANPP, and growth efficiency, as effected by planting density, cultural intensity and site quality <u>during mid-rotation stage</u>

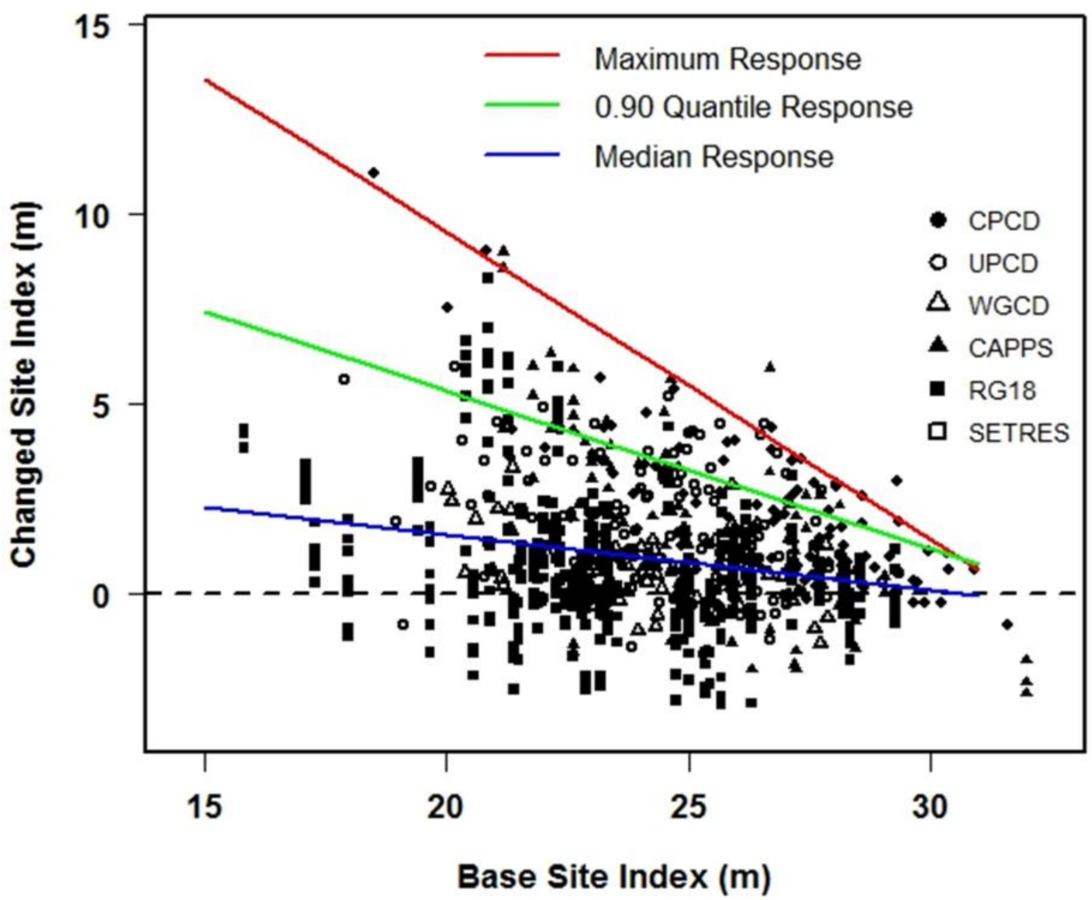
Methods for answering question I



Study	Experimental design	Treatments	Locations	Ages
CPCD study	Split-plot design	Combination of two levels of culture (Operational vs intensive) and six level of planting density (741 – 4448 TPH)	17 locations in GA, FL, SC	18
UPCD study	Split-plot design	Combination of two levels of culture (Operational vs intensive) and six level of planting density (741 – 4448 TPH)	23 locations in GA, FL, SC, AL, MS	16
WGCD study	Split-plot design	Combination of two levels of culture (Operational vs intensive) and five level of planting density (494 –2963 TPH)	18 locations in AR, LA, MS, TX	12
CAPPS study	Randomized complete block design	Fertilization x understory competition control	6 locations in GA	25
RG 18 study	Randomized complete block design	Incomplete factorial of nutrient dose and frequency applied in young plantations	23 trials in AL, FL, GA, LA, MS, NC, SC, VA, TX	16
SETRES study	2 x 2 factorial study	Irrigtion and fertilization	1 location in NC	29

- Data from six long-term studies were analyzed using linear quantile regression to estimate changes in SI as a function of the base SI: $\Delta SI = \beta_0^{(\tau)} + \beta_1^{(\tau)} SI_{base} + \varepsilon^{(\tau)}$
- ΔSI as the difference of the expressed SI of intensive managed plots minus the base SI for a given planting density within the same installation

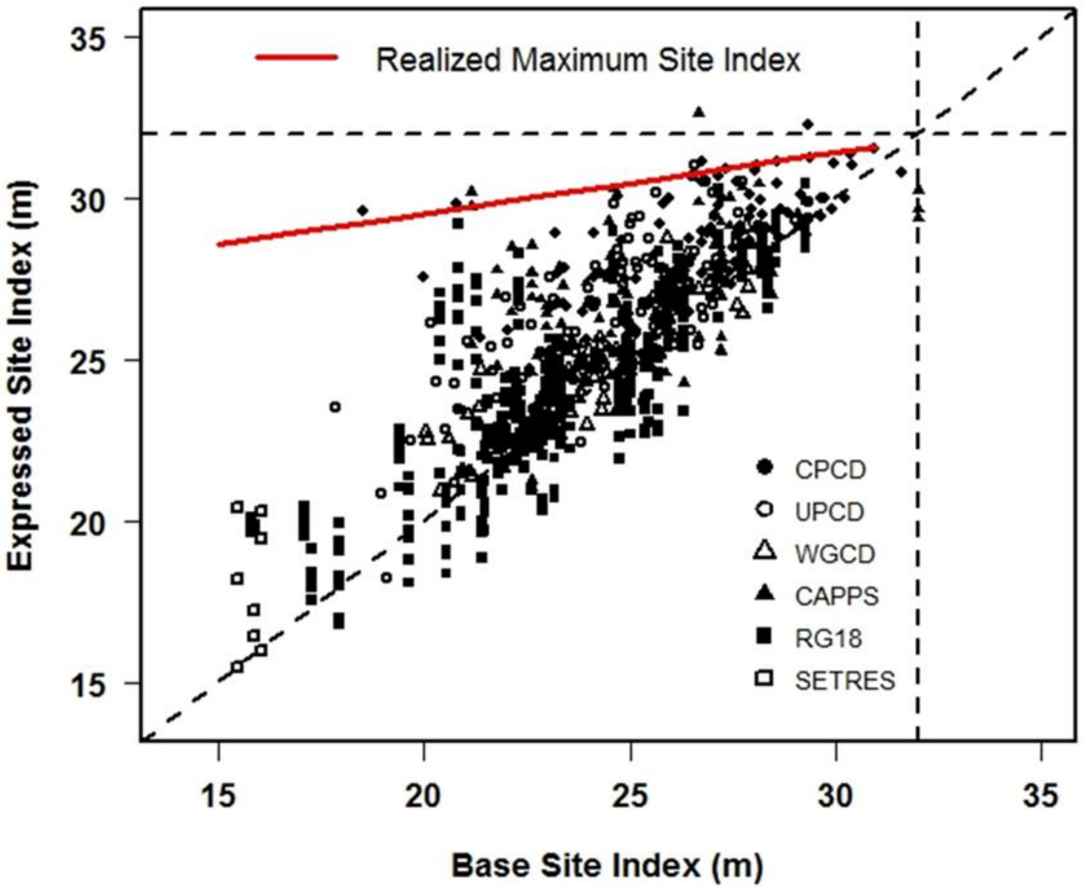
Results – *Maximum Response*



- 26% of the 850 plots that received increased silvicultural inputs did not respond to treatment or even had a negative response.
- The potential SI increase due to silviculture is inversely proportional to the base SI.
  - Higher response on lower quality sites.
- The maximum response line defined by the 0.99 conditional quantile given the base SI

$$\Delta SI = 25.74 - 0.81 SI_{base}$$

Results – *Maximum Response*



- There is a maximum SI for loblolly pine in the South that is around 31 m (100 ft).
- The realized maximum site index: $25.74 + 0.19 SI_{base}$

Sub-summary

- Maximum site index and maximum response mean that the productivity potential and thus carbon sequestration potential of loblolly pine plantations may be finite and can be defined.
- The potential SI increase due to silviculture is inversely proportional to the base SI
- We can optimize silvicultural prescriptions for specific sites (precision silviculture)

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FOREST ECOLOGY AND MANAGEMENT

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

CrossMark

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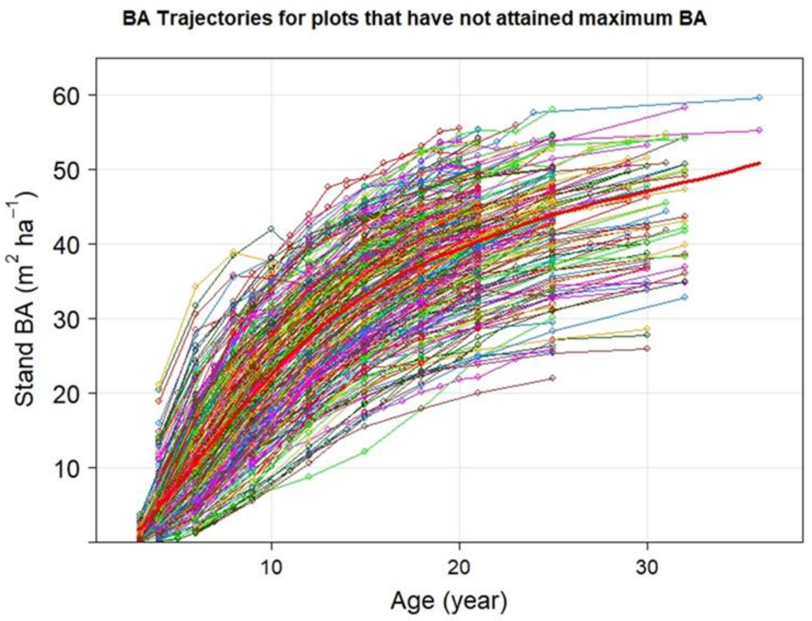
A B S T R A C T

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.

Methods for answering question II – BA_{MAX} & SDI_{MAX}

- BA and SDI of individual stands have similar development patterns: a unimodal curve with a maximal value or an increasing curve with an asymptote
- Thus, BA_{MAX} (or SDI_{MAX}) can be defined as the maximal or asymptotic BA (or SDI) in individual stands



Methods – *Theoretical Analysis*

- First, from relationships among BA-, SDI-, N-, & Dq-A trajectories, we derive the conditions for individual stands to achieve their BA_{MAX} & SDI_{MAX}

$$\frac{\partial SDI/\partial t}{SDI} = \frac{\partial BA/\partial t}{BA} - (2+b)\cdot\frac{\partial Dq/\partial t}{Dq} \quad \text{or} \quad \frac{\partial SDI/\partial t}{SDI} = \frac{\partial N/\partial t}{N} - b\cdot\frac{\partial Dq/\partial t}{Dq}$$

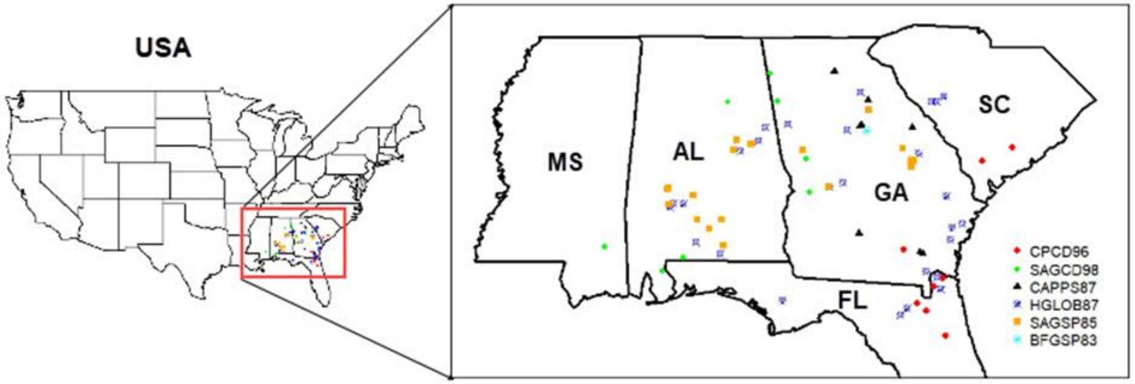
$$BA_{MAX}: \quad \frac{\partial SDI/\partial t}{SDI} = -(2+b)\cdot\frac{\partial Dq/\partial t}{Dq} < 0 \quad \text{or} \quad \frac{\partial N/\partial t}{N} = -2\cdot\frac{\partial Dq/\partial t}{Dq}$$

$$SDI_{MAX}: \quad \frac{\partial BA/\partial t}{BA} = (2+b)\cdot\frac{\partial Dq/\partial t}{Dq} > 0 \quad \text{or} \quad \frac{\partial N/\partial t}{N} = b\cdot\frac{\partial Dq/\partial t}{Dq}$$

- Theoretically proved that stands would achieve their BA_{MAX} only after reaching their SDI_{MAX}

Methods – *Empirical Verification*

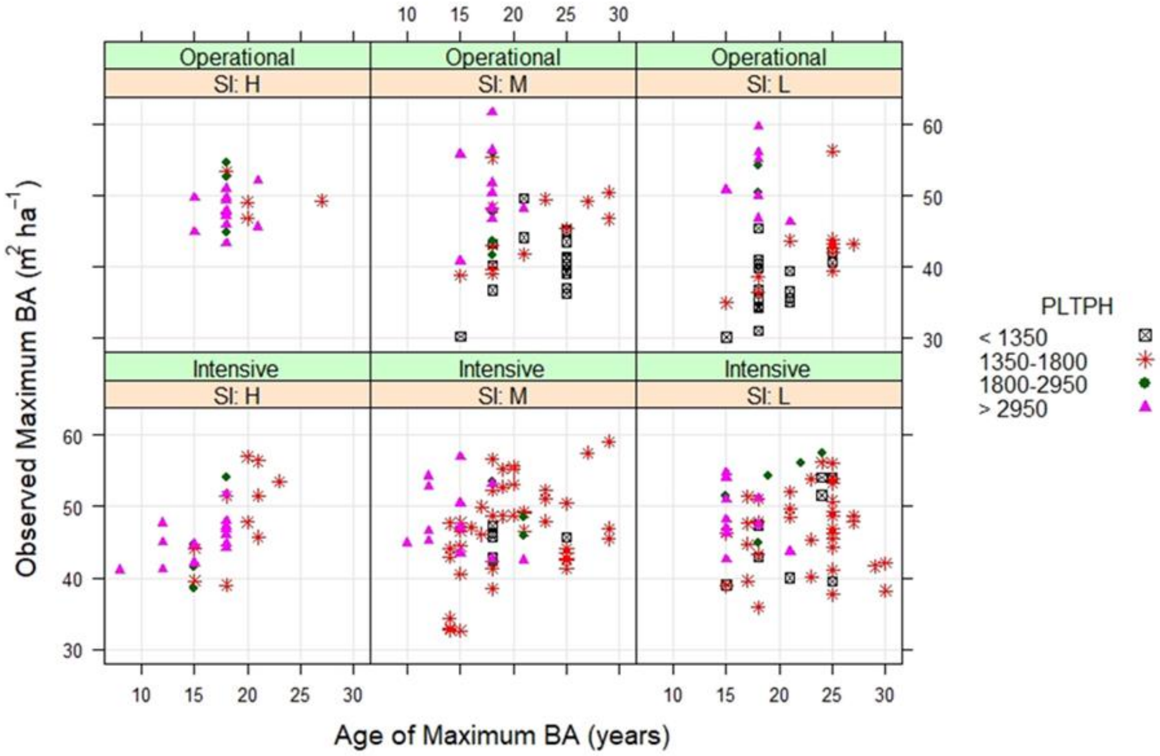
- Then, using six long-term loblolly pine experimental studies to verify these conditions



Study description	Treatments on selected plots	Selected locations	Age	# selected plots
CPCD96: **Culture/Density study**	Combination of two levels of culture (Operational vs intensive) and six levels of planting density (741, 1483, 2224, 2965, 3706, 4448 trees ha^{-1})	8 (GA, FL, SC)	21	82
SAGCD98: **Culture/Density study**	Combination of two levels of culture (Operational vs intensive) and six levels of planting density (741, 1483, 2224, 2965, 3706, 4448 trees ha^{-1})	8 (GA, FL, SC, AL, MS)	21	86
CAPPS87: **Accelerated Pine Production study**	C: no treatment; H: herbicide for complete vegetation control; F: fertilization; HF: herbicide and fertilization treatments. All planted at 1600 trees ha^{-1}	6 (GA)	18-31	120
HGLOB87: **Improved Planting Stock & Vegetation Control study**	Bulk plot improved stock, no vegetation control; Single family improved stock, no vegetation control; Bulk lot improved stock, complete vegetation control; Single-family improved stock, complete vegetation control. All planted at 1790 trees ha^{-1}	29 (GA, FL, SC, AL)	18-30	150
SAGSP85: **Site Preparation study**	C&B: chop and burn; S,P&D: shear, pile and disk; C,H&B: chop, herbicide and burn; H&B: herbicide and burn; H,B&H: herbicide, burn, herbicide. All planted at 1347 trees ha^{-1}	19 (AL, GA, SC)	21-32	105
BFG83: **Spacing study**	Planting density of 495, 989, 1483, 1977, 2471 trees ha^{-1}; complete vegetation control for all plots	1 (GA)	36	8

551 unthinned plots that were planted at the density of ≥ 741 TPH with genetically improved planting stock and last measured at age ≥ 18 years were selected; and grouped into three classes: Low-quality (SI < 24.0 m), Mid-quality (24.0 ≤ SI < 28.0 m), High-quality (SI ≥ 28.0 m)

Results – *Maximum BA & Maximum SDI*



BA_{MAX} ranged 30.2–61.7, average 46.2 m^2 ha^{-1}

A_{BA_MAX} ranged 8–30 years, average 20 years

- With information of site quality, initial density and silvicultural treatments, the magnitude & timing of BA_{MAX} could be estimated:

$$BA_{MAX} = 38.966 + 5.381d_1 + 12.083(d_2 + d_3) - 3.056S_2 + 6.219M - 4.012d_1M + 6.052d_1S_2 - 8.519(d_2 + d_3)M$$

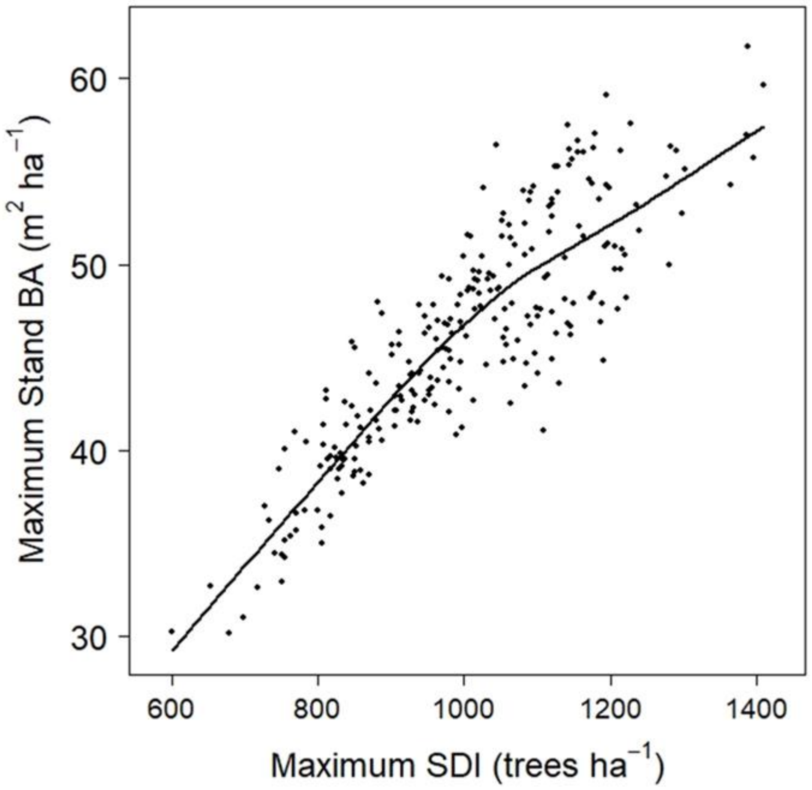
$$A_{BA\_MAX} = 21.779 - 2.768d_2 - 4.407d_3 - 2.156(S_1 + S_2)M$$

$$SI_1 = \begin{cases} 1 & \text{Mid-quality sites} \\ 0 & \text{Other} \end{cases} \qquad SI_2 = \begin{cases} 1 & \text{High-quality sites} \\ 0 & \text{Other} \end{cases}$$

$$d_1 = \begin{cases} 1 & \text{PLTPH}: 1350-1799 \\ 0 & \text{Other} \end{cases} \qquad d_2 = \begin{cases} 1 & \text{PLTPH: 1800 - 2950} \\ 0 & \text{Other} \end{cases} \qquad d_3 = \begin{cases} 1 & \text{PLTPH} > 2950 \\ 0 & \text{Other} \end{cases}$$

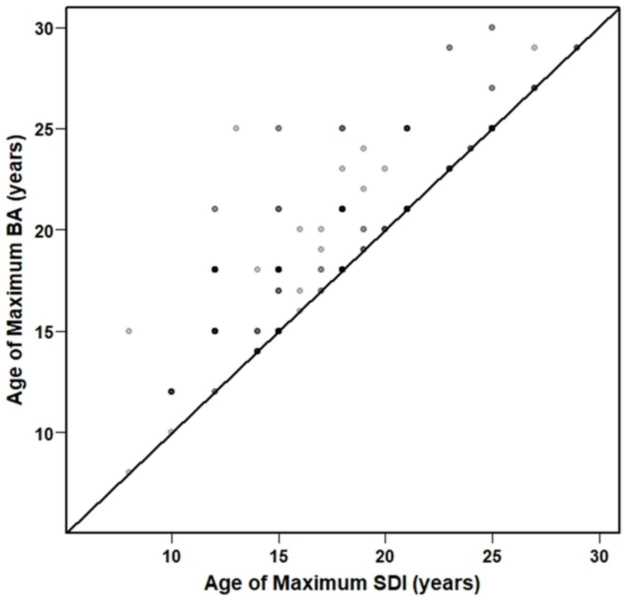
$$M = \begin{cases} 1 & \text{Intensive} \\ 0 & \text{Operational} \end{cases}$$

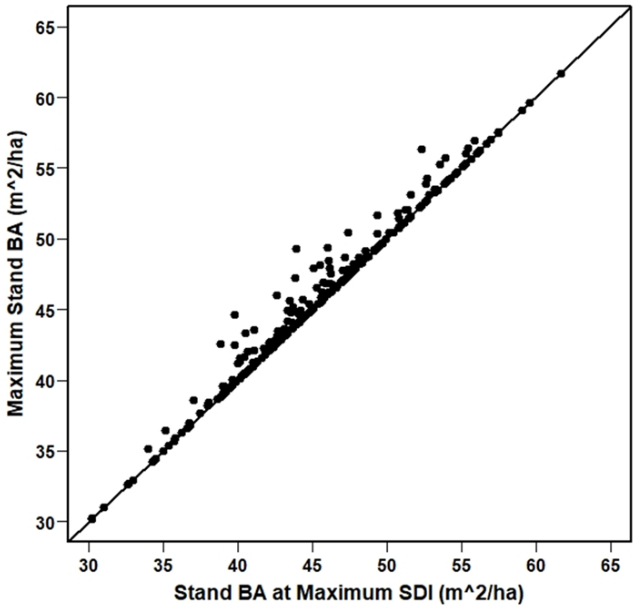
Results – *Maximum BA & Maximum SDI*



- SDI_{MAX} showed significant variation (600–1410 TPH) with an average 1002 TPH
  - Recall, Reineke proposed a SDI_{MAX} of 1110 TPH for loblolly pine
- Stands that achieved higher SDI_{MAX} would achieve higher BA_{MAX}
  - Stand BA & SDI are linked through $Dq^{-(2+b)}$

Results – *Maximum BA & Maximum SDI*





- Comparison of A_{BA_MAX} and A_{SDI_MAX} confirmed that stands would achieve BA_{MAX} when or mostly after achieving their SDI_{MAX}
- Comparison of BA_{MAX} and BA_{SDI_MAX} confirmed that when stands reach their SDI_{MAX}, their BA still increase

Sub-summary

- BA_{MAX} (SDI_{MAX}) is defined as the maximal or asymptotic BA (SDI) in individual stands
- The new definitions could provide a realized carrying capacity for individual stands
- BA_{MAX} ranged 30–62 with a mean 46 m^2/ha
- SDI_{MAX} ranged 600–1410 with a mean 1000 TPH
- The magnitude & timing of BA_{MAX} (or SDI_{MAX}) could be estimated with the information of site quality, initial density, and silviculture

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Rethinking maximum stand basal area and maximum SDI from the aspect of stand dynamics

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Maximum stand basal area
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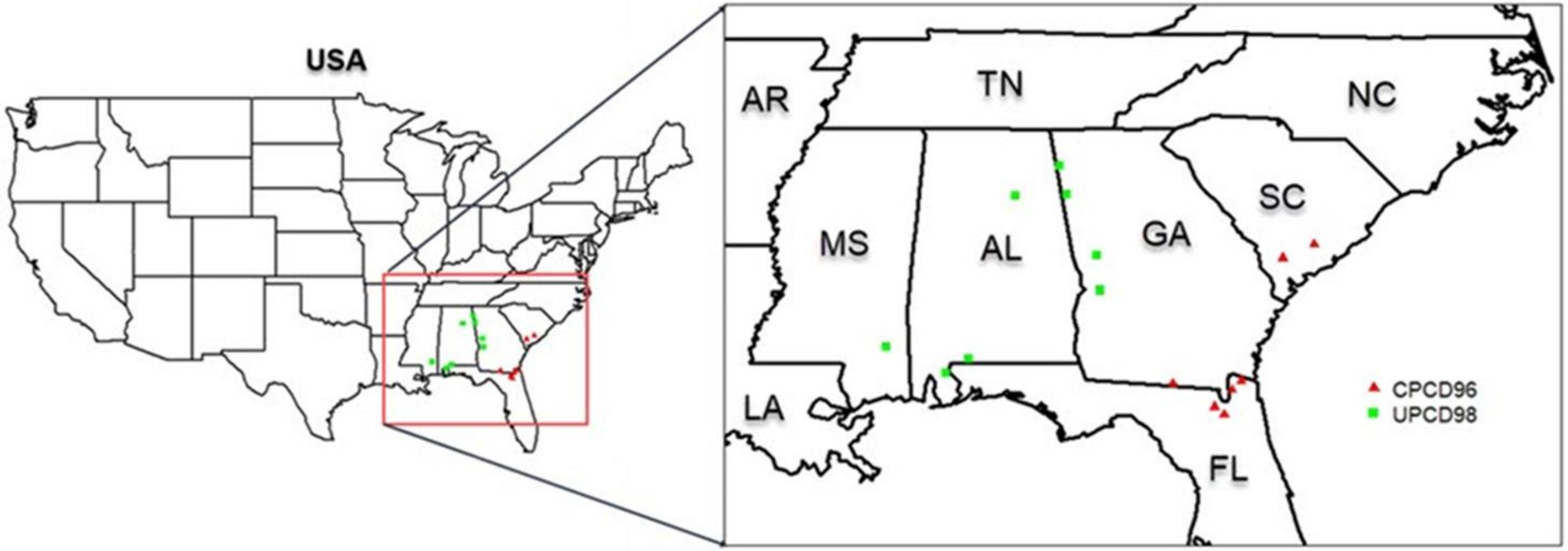
ABSTRACT

The maximum stand basal area (BA) and maximum stand density index (SDI) are often used to express stand carrying capacity in forestry. But their definitions are inconsistent in the literature. The maximum stand BA in most previous studies is associated with an upper boundary for a population of stands and is commonly derived from maximum size-density relationships (MSDRs). The maximum stand BA implied by MSDRs, under the assumption that stands attain maximum BA while attaining maximum SDI, is non-decreasing and divergent. We defined the maximum stand BA and maximum SDI for individual stands based on their BA and SDI development behaviors. Based on the mathematical relationships among stand BA, SDI, thinning, and quadratic mean diameter trajectories and their observed full trajectories in 551 unthinned plots selected from six long-term loblolly pine experimental studies, we theoretically and empirically proved that stands would achieve their maximum BA only after reaching their maximum SDI. The general mean maximum stand BA and maximum SDI for loblolly pine in the southern US were 46.2 m^2 ha^{-1} and 1002 trees ha^{-1}, respectively, and both showed significant variation (30.2–61.7 m^2 ha^{-1} and 600–1410 trees ha^{-1}, respectively). With the information of site quality, initial density and silvicultural treatments, our developed models could estimate the magnitude and timing of maximum stand BA for loblolly pine stands. Insights into individual stand BA and SDI trajectories provide more information for developing site specific silvicultural prescriptions.

Methods for answering question III

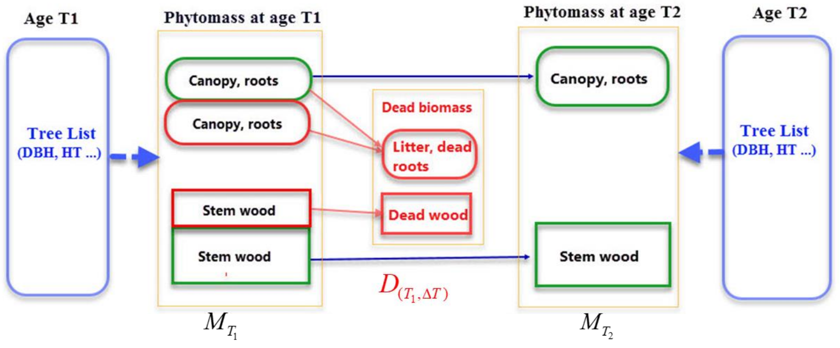
- The relationships between ANPP and crown structure, especially during mid-rotation stage
- 15 non-thinned installations from two culture/density studies



Methods for answering question III

- 2 × 6 plots per installation: 2 levels of cultural intensity (Operational vs. Intensive) and 6 levels of planting density (741, 1483, 2224, 2965, 3706, 4448 TPH)
  - Each tree tagged
  - Measured at 2, 4, 6, 8, 10, 12, 15, 18, 21 years

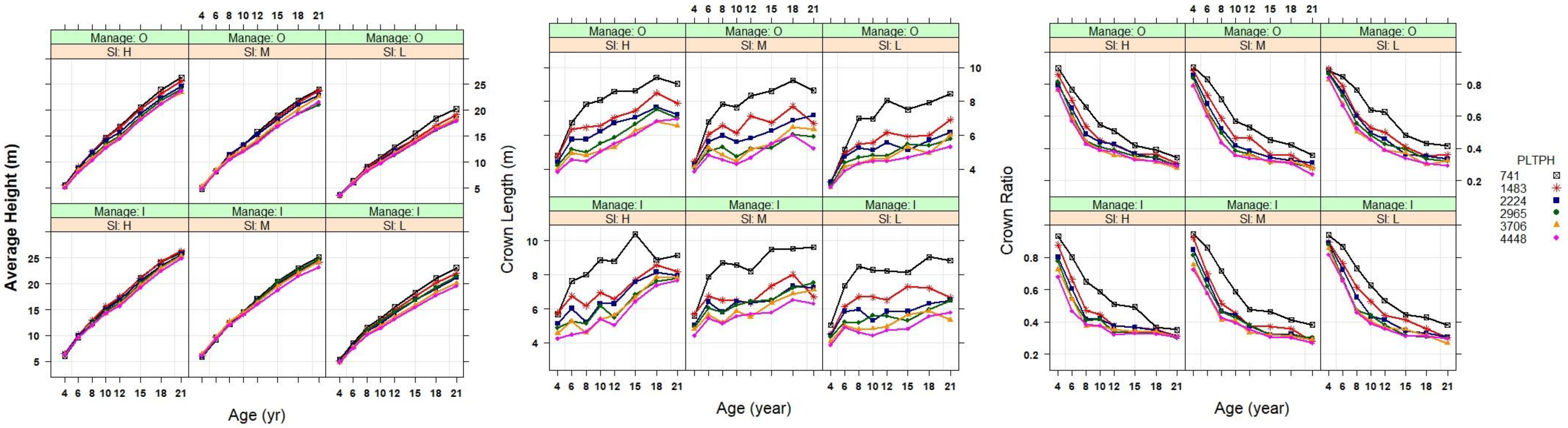
LCP Culture Density Study		UCP Culture Density Study	
Operational	Intensive	Operational	Intensive
Bedding	Bedding	Tillage including subsoiling on some sites	Tillage including subsoiling on some sites
Fall banded chemical site preparation	Fall broadcast chemical site preparation	Broadcast chemical site preparation	Broadcast chemical site preparation
	Tip moth control		
Herbaceous weed control: 1st year banded	Repeated herbicide application to achieve complete vegetation control	Hardwood control: 1st year banded	Repeated herbicide application to achieve complete vegetation control
Fertilization: at planting, 561 kg ha^{-1} of 10-10-10 fertilizer (56 kg ha^{-1} N); before 8th, 12th, 16th, 20th growing seasons, 224 kg ha^{-1} N + 28 kg ha^{-1} P	Fertilization: at planting, 561 kg ha-1 of 10-10-10 fertilizer (56 kg ha^{-1} N); spring 3rd growing season, 673 kg ha^{-1} 10-10-10 + micronutrients + 131 kg ha^{-1} NH_4NO_3; spring 4th growing season, 131 kg ha^{-1} NH_4NO_3; spring 6th growing season, 336 kg ha^{-1} NH_4NO_3; spring 8th, 10th, 12th, 14th, 16th, 20th growing seasons, 224 kg ha^{-1} N + 28 kg ha^{-1} P	Fertilization: at planting, 561 kg ha^{-1} of 10-10-10 fertilizer (56 kg ha^{-1} N); before 8th, 12th, 16th, 20th growing seasons, 224 kg ha^{-1} N + 28 kg ha^{-1} P	Fertilization: at planting, 561 kg ha^{-1} of 10-10-10 fertilizer (56 kg ha^{-1} N); spring 3rd growing season, 673 kg ha^{-1} 10-10-10 + micronutrients + 131 kg ha^{-1} NH_4NO_3; spring 4th growing season, 131 kg ha-1 NH_4NO_3; spring 6th growing season, 336 kg ha^{-1} NH_4NO_3; spring 8th, 10th, 12th, 14th, 16th growing seasons, 224 kg ha^{-1} N + 28 kg ha^{-1} P



$$NPP_{(T_1,T_2)} = M_{T_2} - M_{T_1} + D_{(T_1,\Delta T)}$$

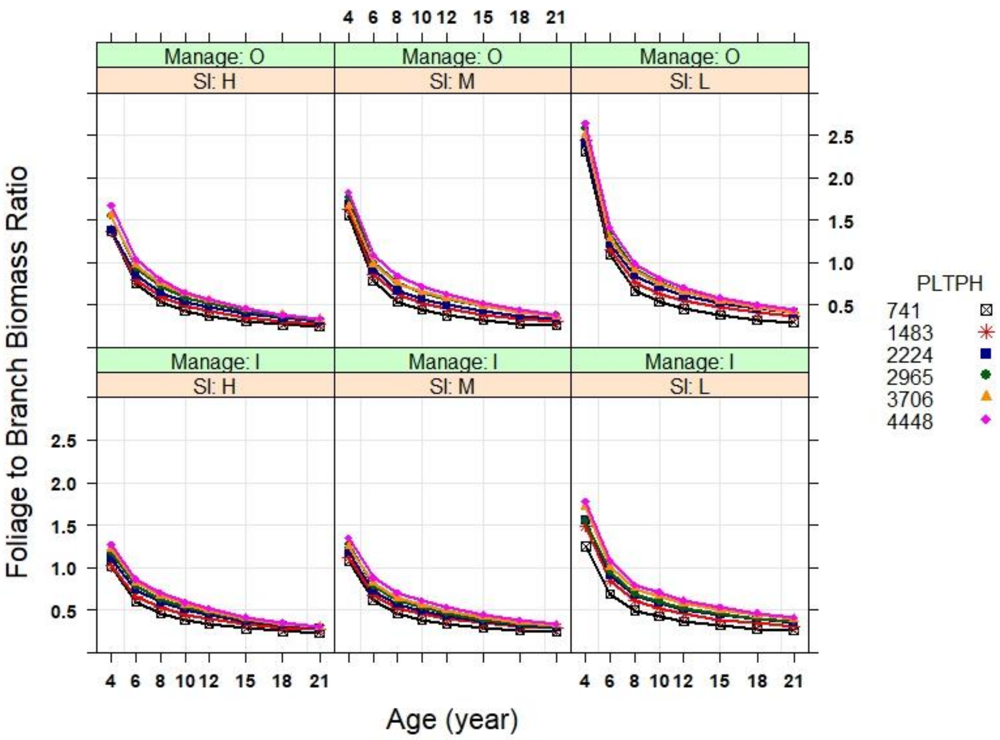
$$NPP_{(T_1,\Delta T)} = \frac{NPP_{(T_1,T_2)}}{\Delta T} = \frac{M_{T_2} - M_{Ns\cdot T_1}}{\Delta T} + \frac{1}{2\theta}\left(Mf_{T_1} + Mf_{T_2}\right)$$

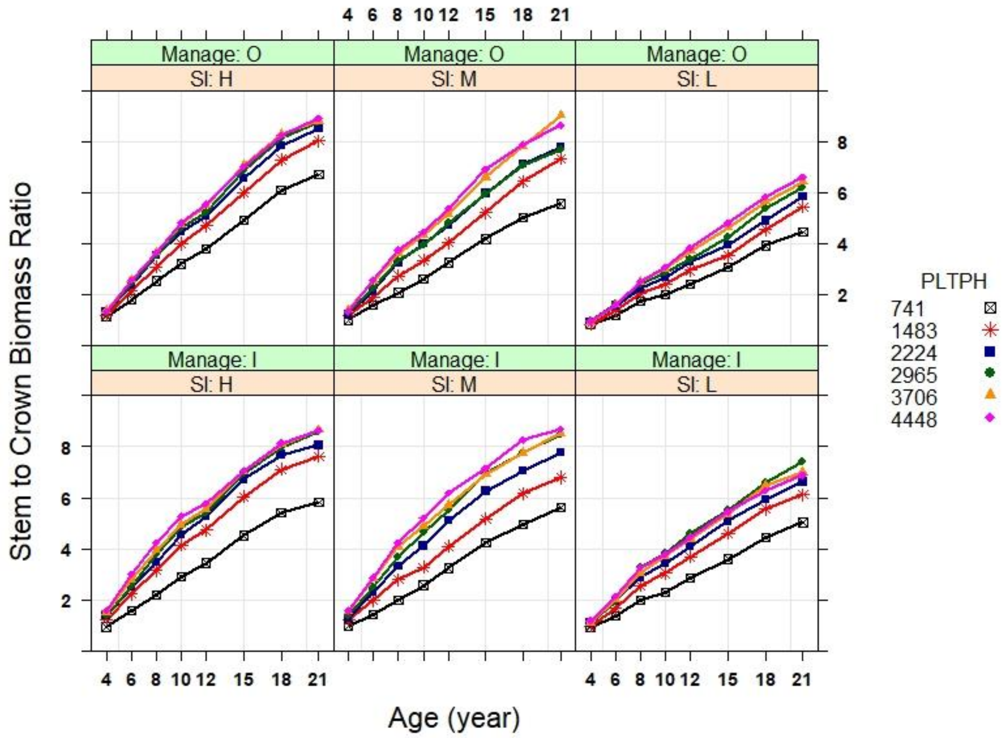
Results – *Average stand height (H), crown length (CL) & crown ratio (CR)*



- More intensive treatments increased both H & CL, did not affect CR
- Stands on higher quality sites had larger H & longer CL, but site quality did not affect CR
- Planting density did not significantly affect H before age 8; after age 10, H decreased with increasing planting density
- Planting density significantly affected CL & CR; lower planting density, longer CL

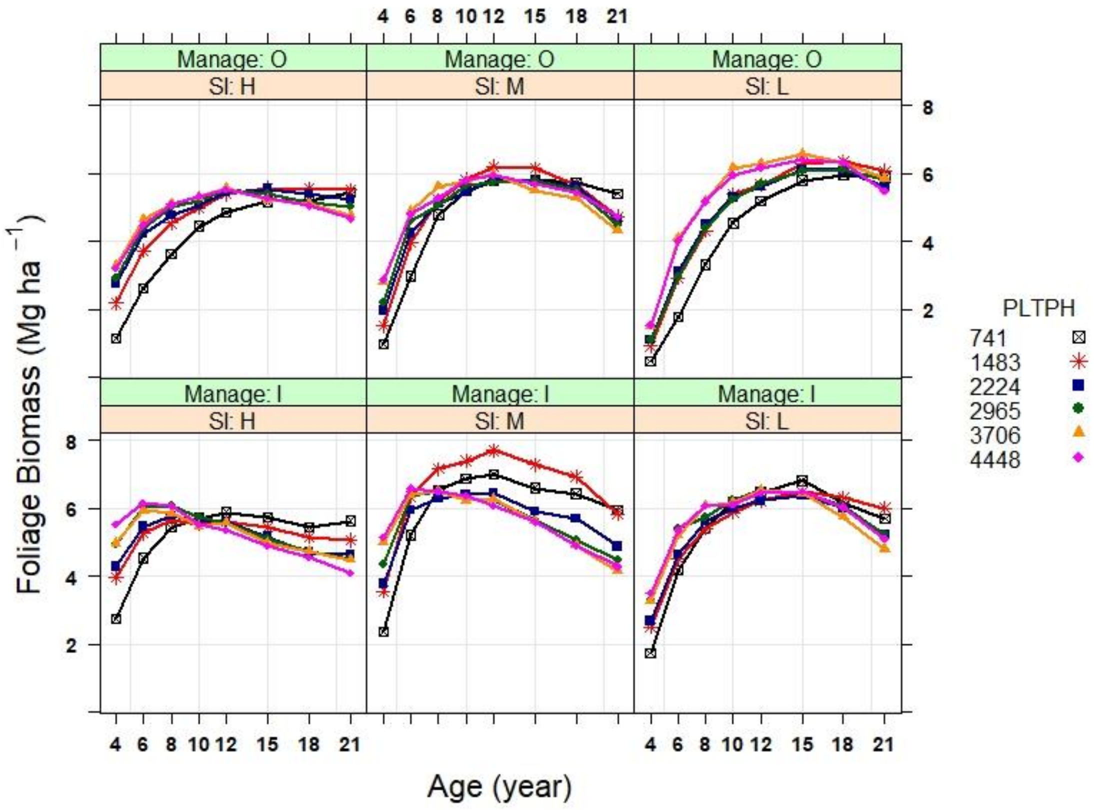
Results – *Foliage to branch biomass ratio (RFB) & stem to crown biomass ratio (RSCB)*





- No significant effects of cultural intensity or planting density on RFB, but site quality significantly affected RFB; stands on higher quality sites had smaller RFB
- RSCB was significantly affected by site quality and planting density, but not by cultural intensity; stands planted at higher densities or on higher quality sites had greater RSCB

Results – *Foliage Biomass (FB)*

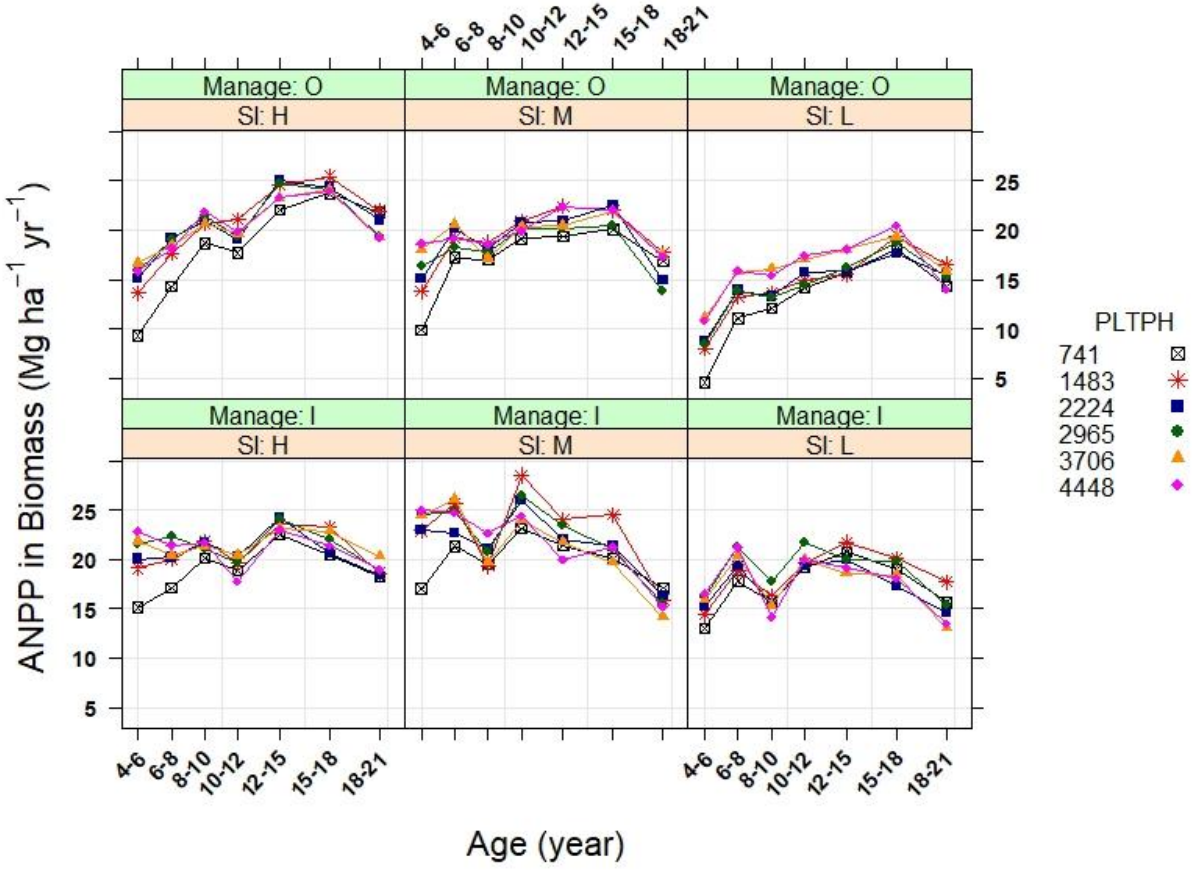


More intensive culture or high-quality sites were associated with more foliage biomass at early ages, thereafter the relationship became more complex

More intensive stands or stands on more productive sites raised to a smaller maximum FB in earlier ages and then flattened

Planting density significantly affected FB in early ages, then not significant in operational stands or on low-quality sites

Results – *Aboveground Net Primary Production (ANPP)*



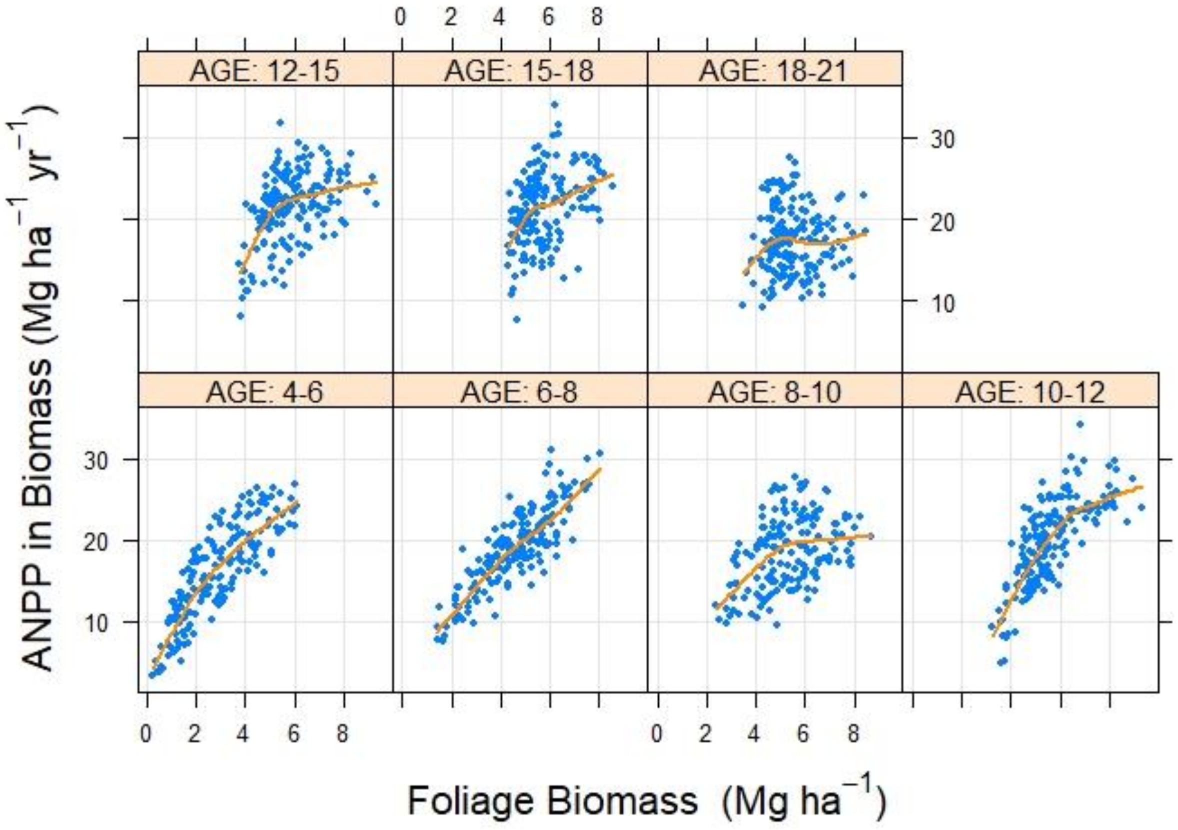
ANPP of operational stands increased over age 4-18 years, thereafter, decreased

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, then the trend did not hold true anymore

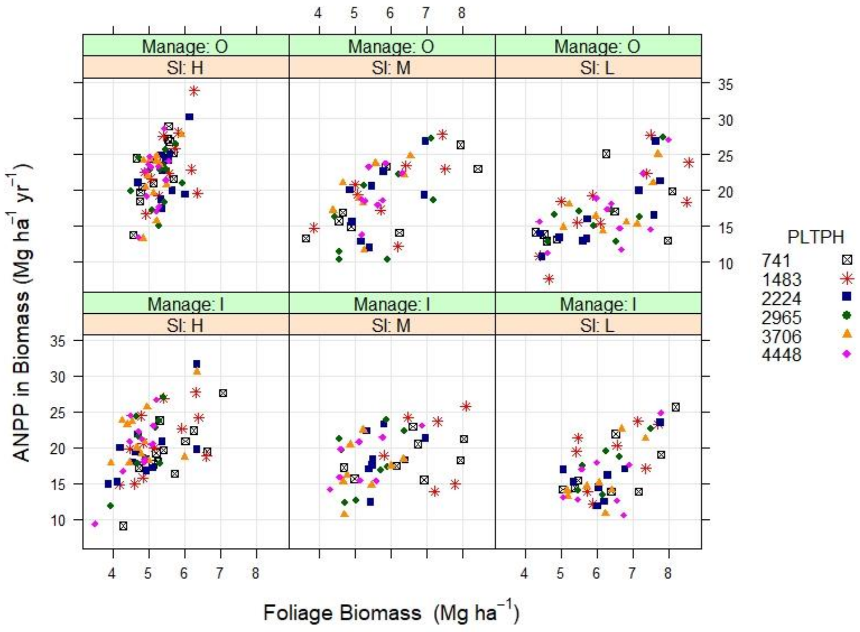
Results – *Relationship between ANPP and FB over time*



Regardless of initial density, culture and site quality, the ANPP-FB relationship was

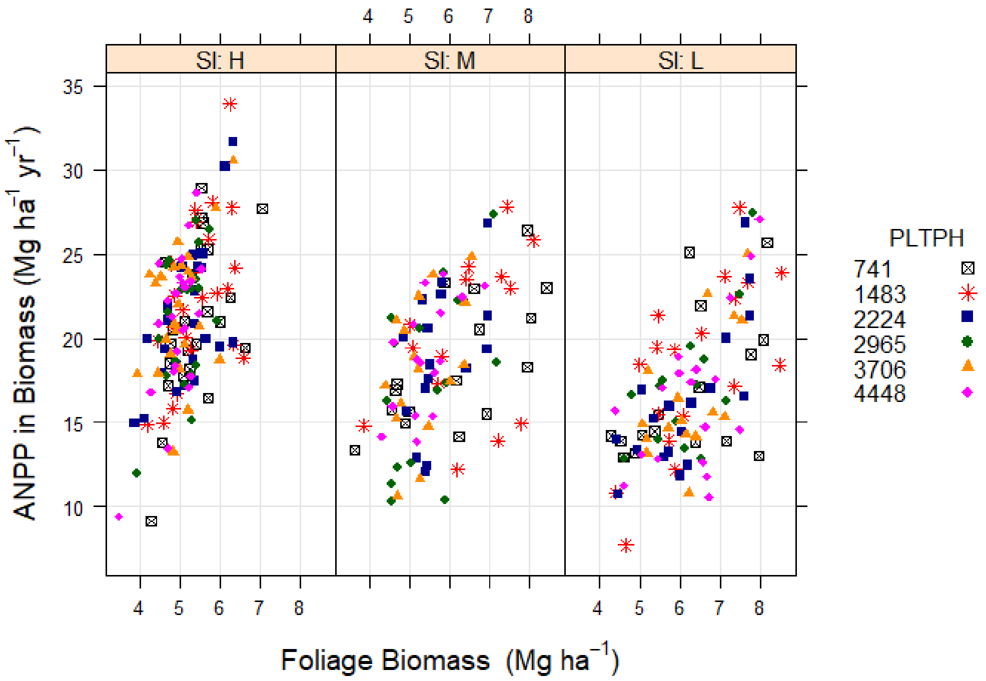
- very strong before age 8 years
- moderately strong over age 8-15 years
- very weak after age 15 years

Results – *Relationship between ANPP and FB after age 15 years*



$$ANPP = 2.628 + 2.878SI_2 + (2.298 + 1.318SI_1)FB$$

After age 15, the ANPP-FB relationship was significantly affected by site quality, but not by culture or planting density.



H: $NPP = 2.628 + 3.616FB$

M: $NPP = 5.506 + 2.298FB$

L: $NPP = 2.628 + 2.298FB$

- Higher growth efficiency on higher quality sites

Sub-summary

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

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Long-term dynamics of loblolly pine crown structure and aboveground net primary production as affected by site quality, planting density and cultural intensity

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Biomass allocation

ABSTRACT

Crown attributes respond readily to silvicultural manipulations and mediate many aspects of stand structure, consequently they dynamically influence stand production. Numerous studies reported crown structure responses to intensive cultures or stand density and the relation between foliage quantity and growth efficiency at early stages of stand development. Long-term temporal patterns of crown structure and its relation to growth have been much less studied. With long-term remeasurement data from two loblolly pine culture-by-density studies, the roles of planting density, cultural intensity and site quality on crown structure, stand aboveground net primary production (ANPP), and growth efficiency were investigated using ANCOVA and linear mixed-effects modeling approaches. Using data from 480 destructively sampled trees, the Dirichlet regression modeling approach was used to analyze foliage and crown biomass allocations among the lower-, middle- and upper-third crown sections. Stands under different cultural intensities showed different temporal patterns of foliage biomass. Increased planting density or higher site quality enhanced wood production of loblolly pine. ANPP generally increased with increasing site quality, due to increased stand foliage biomass in the early stage of stand development, and mainly due to increased growth efficiency in the late stages of stand development. More intensive cultural treatments increased foliage biomass, thus increased ANPP at early ages; thereafter cultural 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. After correcting for the effects of tree size and dominance, cultural intensity still altered the vertical distribution of foliage biomass. More intensive culture resulted in an upward shift of foliage biomass.

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