A COMPARISON OF CANOPY STRUCTURE MEASURES FOR PREDICTING HEIGHT GROWTH OF UNDERPLANTED SEEDLINGS

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Abstract—The study compares the relationship between 15 measures of canopy structure and height growth of underplanted yellow-poplar (*Liriodendron tulipifera* L.) seedlings. Investigators used 4 midstory removal intensities to create a structural gradient across fifty 0.05-ha experimental plots; removals resulted in a range of canopy cover between 51 to 96 percent. Twelve 1-year-old containerized yellow-poplar seedlings were planted within each plot. Height growth was monitored through two growing seasons (2004 to 2005). Investigators used regression analysis (n = 50) to predict 2-year height growth using measures of tree size and density, canopy openness, and vertical structure. Model of best-fit included height to the forest canopy and canopy cover estimated using crown width models ($R^2 = 0.78$). Results emphasize the potential importance of quantifying horizontal and vertical canopy characteristics when evaluating the relationship between forest structure and growth of underplanted seedlings.

INTRODUCTION

Underplanting involves the establishment of nursery grown tree seedlings under an existing forest canopy. The purpose of underplanting is to establish advance reproduction prior to harvest. Underplanting can help supplement natural pools of reproduction or establish high-value species in degraded stands or in stands lacking sufficient seed sources. Unlike the artificial establishment of seedlings following a complete overstory removal, survival and development of underplanted seedlings are influenced by the mitigating effect of the forest canopy on the understory environment (Paquette and others 2006). Existing research shows that field performance of underplanted seedlings is also linked to planting stock quality and size (Dey and Parker 1997a, Spetich and others 2002).

Silvicultural treatments affect the development of underplanted seedlings by altering the understory environment through canopy manipulation. To provide sufficient resources for seedlings, underplanting generally coincides with silvicultural treatments like midstory removal or shelterwood harvest (Dey and Parker 1997b, Johnson 1984, Teclaw and Isebrands 1993). Successful design of these silvicultural treatments is contingent upon understanding interactions between forest structure, understory environment, and physiologic response of forest reproduction. Without considering how the overwood influences growth and mortality of underplanted seedlings as well as their competitors, the success of underplanting operations may be limited. Quantitative approaches linking seedling growth to stand structure are important because they can help silviculturists develop appropriate residual density recommendations that can be practically applied by field foresters.

Our objective is to identify measures of canopy structure that can be used to predict initial height growth of underplanted seedlings along a gradient of partial harvest conditions. We present height growth models for underplanted yellow-poplar (*Liriodendron tulipifera* L.) developed using two groups of predictor variables: (1) all measures of canopy structure evaluated and (2) only measures of canopy structure that can be derived from tree inventory data. We hypothesize that models will incorporate measures of canopy structure and seedling size. Based upon published relationships between forest structure and the understory environment (Lhotka and Loewenstein 2006), we further hypothesize that the seedling growth models will include variables describing horizontal and vertical characteristics of the forest canopy.

METHODS

Site Description

The study was conducted within the riparian forest corridor of a 450-ha watershed in Harris County, GA (approximately 32° N, 85° W). The site is within the lower Piedmont physiographic region. The overstory was primarily composed of yellow-poplar and sweetgum (*Liquidambar styraciflua* L.). Water oak (*Quercus nigra* L.), green ash (*Fraxinus pennsylvanica* Marsh.), and boxelder (*Acer negundo* L.) are minor components of the stand. A dense midstory was present across much of the area, dominated by flowering dogwood (*Cornus florida* L.), two-wing silverbell (*Halesia diptera* Ellis), musclewood (*Carpinus caroliniana* Walt.), and ironwood [*Ostrya virginiana* (Mill.) K. Koch]. The understory was primarily composed of Japanese honeysuckle (*Lonicera japonica* Thunb.), Nepalese browntop [*Microstegium vimineum* (Trin.) A. Camus], and blackberry (*Rubus* spp.). No flooding occurred during the duration of this study.

Study Design

In August 2003, fifty 0.05-ha circular plots were established within portions of the riparian forest corridor that were at least 38 m wide. Plots were systematically located along a transect bisecting this corridor and a minimum of 38 m separated each plot center. To ensure that all plots were located under closed canopy conditions, establishment criteria ensured that all plot centers were not less than 19 m from the edge of the riparian corridor and not less than 12.6 m from a forest gap.

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Investigators created a canopy cover gradient across the 50 plots by randomly assigning 1 of 4 midstory removal treatments: (1) no midstory trees removed, (2) one-third of all midstory trees removed, (3) one-half of all midstory trees removed, and (4) complete midstory removal. Midstory trees were defined as stems not present in the dominant/codominant canopy layer. Structural manipulations were completed using directional chainsaw felling between August and October of 2003. Vegetation <1.4 m tall was not removed unless it created a safety hazard during felling operations. No trees were removed from the site but were cut up to facilitate underplanting and to speed decomposition. Following midstory treatments, twelve 1-year-old containerized yellow-poplar seedlings were planted within each plot. Seedlings were planted in a systematic grid located within the inner portion (6.31 m from plot center) of each plot. This planting area was selected so that the outer half of the plot could help buffer the effects of plot edge on the response of planted seedlings. All planting occurred between October and November of 2003. Readers should note that the yellow-poplar seedlings sustained wind damage at the nursery during the middle of the growing season and that the nursery manager ameliorated damage by top clipping seedlings to a uniform height. By fall planting, seedlings had new stem growth and a fully developed terminal bud.

Data Collection and Analysis

Seedling growth was monitored over two growing seasons (2004 and 2005), and seedling inventories were completed prior to budbreak in the spring of 2004 and after final terminal bud formation in the fall of 2004 and 2005. At each inventory, basal diameter (mm), height (cm), and survival status were recorded for the planted seedlings. To link growth of underplanted seedlings to canopy structure, metrics of canopy openness, stand density, tree size, and vertical structure were quantified.

Following midstory treatment, overstory tree inventories were completed for each 0.05-ha plot. All trees >5 cm d.b.h. were measured and total height (m), height (m) to the base of the live crown (HBLC), d.b.h. (cm), and species were recorded. Tree inventory data were summarized to determine density (trees/ha), basal area (m^2/ha), and quadratic mean diameter (cm). Measures of vertical structure were derived from tree inventory data including average HBLC, average tree height, top height, and average canopy depth (e.g., average tree height – average HBLC). Vertical structure of each plot was also characterized by measuring height to the forest canopy (m) above each seedling. Height-to-canopy was defined as the vertical distance (m) from a seedling to the nearest overhead tree crown. Vertical distances were measured using a Vertex III digital hypsometer.

In the summer of 2004, investigators quantified canopy openness using measures of percent canopy cover and canopy closure for each plot. A GRS Densitometer (Geographic Resource Solutions, Arcata, CA) was employed to estimate canopy cover using the vertical sighting tube method (Johansson 1985). Observations were taken on 2- by 2-m grid with a total of 113 points located on each plot. The instrument was leveled at every sample point and the presence or absence of canopy was tallied. Percent cover was calculated by dividing the number of points where canopy was present by the total number of sample points. Canopy cover was also estimated using tree inventory data and species-specific crown width models. Calculating canopy cover using crown area projection involved three computational steps. Allometric crown width models were used to estimate each tree's horizontally projected crown area (Bechtold 2003). These estimated crown areas were then summed to determine a plot's total projected crown area (CA_{tot}). Finally, percent canopy cover was determined by inputting CA_{tot} into the crown overlap correction function (equation 1) presented by Crookston and Stage (1999).

$$\text{Percent canopy cover} = 100\left(1 - \exp\left(-0.01 \times 100 \times \frac{CA_{tot}}{10000}\right)\right) \quad (1)$$

where
exp = exponential function
CA_{tot} = plot's total projected crown area

Canopy closure was estimated using a convex spherical densiometer. Readings were taken directly over plot center in each cardinal direction and average closure was recorded (Buckley and others 1999). Because research suggests that observer effect can introduce bias into densiometer readings (Vales and Bunnell 1988), a single individual collected the data. Hemispherical photography was also used to quantify canopy closure (Jennings and others 1999). One photograph was taken 1.25 m above each plot center using a Nikon Coolpix 5700 (5 megapixel) digital camera and fisheye converter (183° view angle). Although research suggests that digital and film hemispherical photography can yield comparable results (Englund and others 2000, Hale and Edwards 2002), factors such as digital image size, compression, quality, and saturation can influence the analysis of digital fisheye photos. To minimize these issues, the following camera settings were used: (1) image quality—1 to 4 compression JPEG format, (2) saturation—black and white, and (3) image size—full (2,560 by 1,920 pixels) (Frazer and others 2001). Additionally, all photos were taken during overcast conditions when the solar disk was completely obscured. The camera was leveled and the fisheye lens oriented toward magnetic north using a compass prior to each shot. Visible sky proportion was obtained from the hemispherical photographs by using Hemiview software (Delta-T Devices Ltd., Cambridge, UK) and canopy closure (1—visible sky proportion) was calculated. Threshold pixel classification of "sky" vs. "canopy" was set individually for every photo; one operator completed all analyses. Photo analysis was completed at four view angles 180°, 120°, 90°, and 60° by constraining the proportion of the photo processed by Hemiview.

The goal of our analysis was to determine the relationship between the measures of forest canopy structure and the 2-year growth of underplanted yellow-poplar seedlings. Analysis was completed at the plot level and used average 2-year (2004 to 2005) height growth by plot (n = 50) as the response variable. The predictor variables evaluated included metrics of tree size and density, canopy openness, and vertical structure (table 1). Simple linear regression was

Table 1—Descriptive statistics for plot-level canopy structure and underplanted seedling data (*n* = 50)

Plot-level variables	Mean	Minimum	Maximum	Standard deviation	*R*-square[a]
Quadratic mean diameter (cm)	31.60	14.38	60.67	10.58	0.37
Density (trees/ha)	569.20	120.00	1860.00	371.30	0.44
Basal area (m^2/ha)	34.85	12.91	62.85	9.20	0.09
Top height (m)	32.24	25.94	39.57	3.89	0.12
Tree height (m)	21.43	11.44	38.76	6.77	0.40
Height to the base of live crown (m)	10.53	4.76	20.94	3.90	0.32
Canopy depth (m)[b]	21.72	13.12	31.27	3.93	0.35
Height to the forest canopy (m)	14.23	2.35	30.92	6.32	0.68
Percent cover—vertical sight tube	84.04	51.32	95.57	8.76	0.36
Percent cover—crown width models	77.24	56.20	92.72	9.55	0.60
Closure—spherical densiometer	0.91	0.75	0.96	0.05	0.45
Closure—photo angle 180	0.92	0.90	0.95	0.01	0.31
Closure—photo angle 120	0.87	0.80	0.92	0.03	0.19
Closure—photo angle 90	0.82	0.71	0.89	0.05	0.16
Closure—photo angle 60	0.79	0.60	0.91	0.07	0.11
Mean seedling diameter at planting (cm)	8.01	6.34	9.52	0.78	0.01
Seedling 2-year height growth (cm)	68.98	17.50	177.60	35.84	1.00

[a] Coefficient of determination (R^2) for relationship between the given variable and 2-year (2004–05) height growth (cm) of underplanted yellow-poplar seedlings.

[b] Canopy depth = (average tree height – average height to base of live crown).

used to quantify the relationship between each canopy structure measure and 2-year height growth. Next, multiple regression was used to construct best-fit models from two groups of variables. The first set of models evaluated each of the forest structural metrics reviewed by the study and the second incorporated only variables derived from tree inventory data. Given known relationships among canopy structure, understory microclimate, and tree ecophysiology (Assenac 2000), we hypothesized that best-fit models would include measures of canopy openness, vertical structure, and a measure of seedling size at planting. Average initial basal diameter was used as the measure of seedling size. Goodness-of-fit was evaluated using the coefficient of determination, commonly referred to as R^2 (Neter and others 1996). A Box-Cox power transformation (equation 2) was used to meet homogeneity of variance and normality of residuals assumptions (Ott 2005). Box-Cox transformation power (λ) was determined in SAS using PROC Transreg.

$$Y_t = \frac{Y_i^{\lambda} - 1}{\lambda} \quad (2)$$

where
Y_t = Box-Cox power transformed observation
Y_i = observed value
lambda (λ) = Box-Cox transformation power

For models of best-fit, variance inflation factor (VIF) was used to evaluate multicollinearity. Any variable with a VIF greater than 10 was removed from the model (Neter and others 1996).

RESULTS AND DISCUSSSION

Our goal was to determine the relationship between the measures of forest canopy structure and the 2-year growth of underplanted yellow-poplar seedlings across a gradient of partial harvest conditions. The random application of four midstory removal intensities was successful at creating a canopy structure gradient across the experimental plots. The canopy cover gradient was between 51 and 96 percent. Height to the forest canopy (height-to-canopy) ranged from 2 to 31 m and residual basal area was between 12 and 63 m^2/ha.

Of the variables evaluated in this study, height-to-canopy (R^2 = 0.68) and canopy cover estimated using crown area projection (R^2 = 0.60) were most strongly related to height growth of the underplanted yellow-poplar seedlings. Other variables that explained >30 percent of the variation in 2-year height growth included: (1) spherical densiometer estimates of canopy closure, (2) stand density, (3) average tree height, (4) vertical sighting tube estimates of canopy cover, (5) average canopy depth, (6) average HBLC, and (7) hemispherical photo derived canopy closure (180° view angle) (table 1).

Models of best-fit were developed using two groups of predictor variables: (1) all measures of canopy structure evaluated and (2) only measures of canopy structure that can be derived from tree inventory data. The model developed for each group of variables explained at least 70 percent of the variance in 2-year height growth and included canopy cover estimated using crown area projection and a measure of vertical structure (equations 3 and 4). The presented models support our hypothesis that variables describing both horizontal and vertical canopy structure are needed to adequately predict seedling growth. Unlike our hypothesized model structure, average seedling size (basal diameter) was not a significant predictor of height growth at the plot level. This may have been due to the relative uniformity of the planting stock.

Model of best-fit (R^2 = 0.77)

$$\text{height growth}_{\text{Trans}} = 11.8542 + 0.1541\,(\text{height-to-canopy}) - 0.0753\,(\text{canopy cover}_{\text{CA}}) \quad (3)$$

Tree inventory based model (R^2 = 0.70)

$$\text{height growth}_{\text{Trans}} = 15.5557 - 0.1190\,(\text{canopy cover}_{\text{CA}}) + 0.1714\,(\text{average canopy depth}) \quad (4)$$

where

$\text{height growth}_{\text{Trans}}$ = Box-Cox transformed 2-year height increment with a lambda transformation power of 0.30

$\text{canopy cover}_{\text{CA}}$ = percent canopy cover estimated using crown area projection

height-to-canopy = average height (m) to the forest canopy above underplanted seedlings

average canopy depth = average tree height – average height to the base of live crown

Models suggest that average 2-year height growth increases as height-to-canopy increases and canopy cover decreases (fig. 1). Because midstory removal and/or shelterwood harvests decrease canopy cover and increase the vertical distance between the forest floor and the canopy (Loftis 1990), results of this study support the application of these treatments as a method for enhancing height growth of underplanted yellow-poplar seedlings. Trends presented in figure 1 could be used to determine the average height growth response that may result from any given residual height-to-canopy and canopy cover combination. While models explained more than 70 percent of the variance in 2-year height growth, lack of site replication across the landscape limits the applicability of the presented models. However, the outlined methodology may serve as a framework for the development of quantitative approaches that link growth of underplanted seedlings to variables describing the stand structure. A model based solely on metrics derived from tree inventory data could potentially be linked with a stand development model, e.g., Forest Vegetation Simulator, to evaluate how residual structure affects seedling response. This linkage may allow managers to evaluate how a suite of silvicultural practices affect growth of underplanted seedlings, to identify a target residual structure, and to produce stand structure-based marking prescriptions that can be implemented by field foresters. Finally, results emphasize the potential importance of quantifying horizontal and vertical canopy characteristics when evaluating the relationship between forest structure and growth of underplanted seedlings.

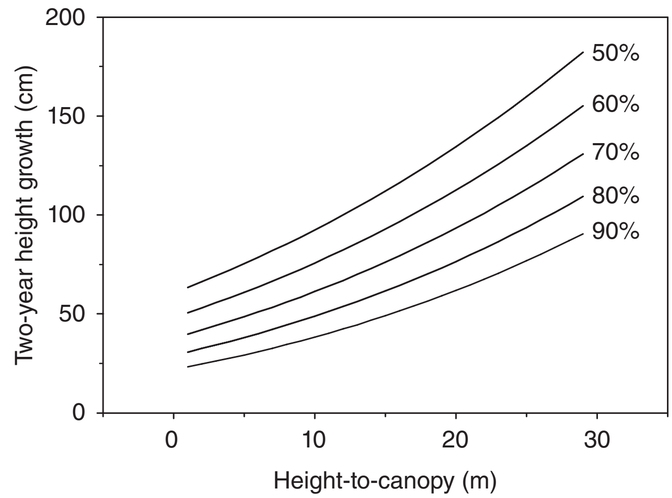

Figure 1—Generalized relationship between height-to-canopy and 2-year (2004 and 2005) height growth of underplanted yellow-poplar seedlings at five levels of canopy cover. The height-to-canopy and canopy cover array used to estimate height growth trends fall within the study's observed data range.

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