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Using segmented regression to model the density–size relationship in direct-seeded slash pine stands

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Abstract

This study investigated the application of segmented regression techniques to modeling the trajectory of tree density and quadratic mean diameter through time for individual stands. The full model contains three segments for characterizing the three different stages of the trajectory on a log–log scale. The first segment represents precanopy conditions where no mortality is expected after what normally occurs before initial tree establishment. The next two segments are quadratic functions to accommodate two distinct mortality rates if present in the trajectory. Quadratic functions were selected based on published trajectories for loblolly pine (*Pinus taeda* L.) and slash pine (*Pinus elliottii* var. *elliottii* Engelm.) in southeastern U.S. A reduced model is formed by simply joining two quadratic segments. Data from direct-seeded slash pine stands used in this study fit the reduced model. The two-segment model requires a join point, which was predicted as a power function of the logarithm of initial stand density. The resulting trajectories matched observed trends in the data reasonably well. The segmented regression approach is appealing for modeling very complicated functional forms such as the density–size relationship presented in this paper.

Keywords: Size–density trajectory; *Pinus elliottii*; Self-thinning; Mortality rate

1. Introduction

Depending on the objective, modelers have used various approaches to quantitatively describe the growth trajectory of an even-age monoculture in terms of either average stand diameter or mean stem volume and number of trees per hectare under the constraint of a limiting relationship between mean size and tree number (e.g., Smith and Hann, 1984; Puettmann et al., 1993; Tang et al., 1994). The constraint originates from observations of even-age monocultures asymptotically approaching a linear boundary between the log of mean tree size and the log of spatial density. This observation is not universal, however, as other data suggests a curvilinear trajectory throughout the lifespan of a stand, at least for loblolly and slash pine (Zeide, 1987; Cao et al., 2000).

One of the incentives for modeling the size–density trajectories of individual stands is that it eliminates the need to censor data to investigate the properties of the upper boundary of the tree size and tree density relationship; the boundary emerges from overlapping trajectories of individual stands (Smith and Hann, 1986). Another advantage of individual trajectories is their incorporation into stand growth models (e.g, Tang et al., 1994). To fully benefit from this technique the models need to accurately describe the life-long developmental trajectories of the stand. Even-age monocultures move through several stages of development, each with characteristic mortality rates which influence accuracy of quantitative descriptions of the trajectory. Modelers have assumed a monotonic increase in mortality with increasing proximity to the size–density boundary after canopy closure. In addition, Long and Smith (1984) proposed an intervening developmental stage between canopy closure and self-thinning called full-site occupancy that is characterized by hastened size differentiation among trees in the stand and skewness in size distribution. Pre- and postcanopy closure mortality rates suggest that a complete description of a stand's developmental trajectory requires at least two distinct curve segments; an intervening developmental stage may indicate the need for a third segment. The objective of this study was to apply segmented regression techniques to modeling the trajectory of stand density and quadratic mean diameter of individual stands through time.

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Table 1
Distribution of 147 permanent plots in direct-seeded slash pine stands, by measurement ages

Stand age (years)		Number of plots
First measurement	Last measurement	
8	17	1
8	19	18
8	20	10
8	23	25
8	27	24
9	15	1
9	18	3
9	20	3
9	28	8
10	25	20
11	22	17
12	27	12
13	28	5

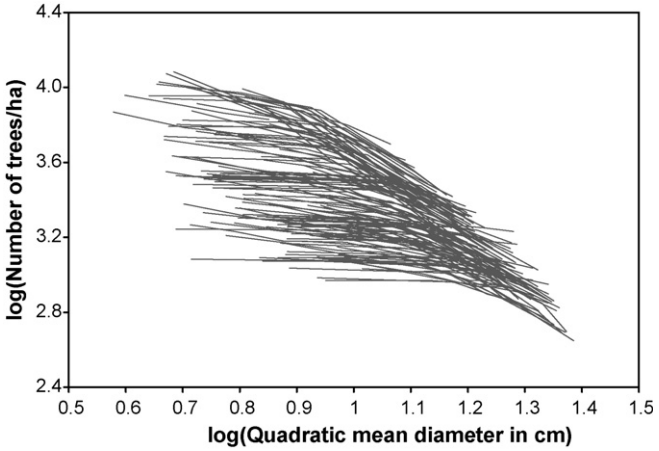

Fig. 1. Density–size trajectories observed from 147 permanent plots in direct-seeded slash pine stands.

2. Data

Data available for this study were from 147 permanent plots from direct-seeded slash pine (*Pinus elliottii* var. *elliottii* Engelm.) stands on cutover sites located in Natchitoches and Rapides parishes (central Louisiana) and in Washington parish (southeast Louisiana). A detailed description of the data can be found in Baldwin (1985) and Lohrey (1987). Plot size ranged from 0.040 to 0.048 ha. Some plots were precommercially thinned at age 3 or 4 years. Stand age ranged from 8 to 28 years, stand density from 445 to 12,108 trees/ha, basal area from 2.6 to 52.6 m^2/ha, and site index (base age 25 years) from 9 to 23 m. Distribution of plots by measurement ages is presented in Table 1. Each plot was measured from three to six times, at 3–10 years apart, resulting in a total of 615 measurements encompassing 468 growth periods. Table 2 shows the mean and standard deviation of number of trees per hectare and quadratic mean diameter for each measurement age. The trajectories of stand density and quadratic mean diameter for these measurements are shown in Fig. 1.

3. Methods

Segmented regression models have been employed to describe complicated functional forms such as tree taper (Max and Burkhart, 1976; Fang et al., 2000; Coble and Hilpp, 2006) and the height–age relationship (Devan and Burkhart, 1982; Borders et al., 1984). Similar techniques were recently used to determine what observations of size–density trajectories were within particular stages and phases of stand development (VanderSchaaf and Burkhart, in press). In this study, segmented regression techniques were applied to model trajectories of stand density and quadratic mean diameter through time.

Table 2
Mean (and S.D.) of number of trees per ha and quadratic mean diameter measured through time from 147 permanent plots in direct-seeded slash pine stands

Age	Number of plots	Stand density (number/ha)	Quadratic mean diameter (cm)
8	78	3715 (2733)	6.7 (1.5)
9	15	2112 (996)	6.7 (1.5)
10	20	2409 (860)	9.1 (1.0)
11	53	3201 (2410)	9.2 (3.0)
12	35	4583 (2657)	8.5 (1.8)
13	34	3251 (2099)	9.9 (2.2)
14	53	2736 (2078)	11.3 (3.4)
15	24	1604 (500)	13.8 (1.4)
17	71	3161 (2165)	12.0 (3.5)
18	34	2493 (1610)	12.8 (2.7)
19	18	1848 (786)	15.0 (2.2)
20	20	1250 (662)	17.9 (2.6)
22	53	2794 (1343)	12.8 (2.7)
23	38	1735 (1316)	16.5 (3.6)
25	20	799 (220)	21.3 (1.5)
27	36	2087 (624)	16.0 (2.3)
28	13	2420 (1269)	15.1 (2.7)