Effects of silvicultural treatments on temporal variations of spatial autocorrelation in Eucalyptus plantations in Brazil

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ABSTRACT

We examined the change in spatial structures of Eucalyptus plantations across different types of silvicultural treatments over a full rotation. Clonal and seed-origin Eucalyptus plots applied with differing levels of fertilization (high vs. traditional) and irrigation (irrigated vs. non-irrigated) treatments were investigated. Additionally, for the clonal plots, uniform vs. heterogeneous stand structure treatments were created using staggered planting dates. The heterogeneous structure of the clonal plots aimed to mimic the seed-origin plots. Spatial structures were characterized by assessing the spatial autocorrelations of diameters, heights, and biomass. We also applied two distance-based neighborhood structures to look at the degree of change in spatial autocorrelations with different numbers of neighboring trees being defined as neighbors. The results suggest that spatial autocorrelations of diameters, heights, and biomass of Eucalyptus plantations were mostly insignificant at an alpha level of 0.05 over the rotation. However, spatial autocorrelations in most plots after the middle of the rotation were predominantly negative, indicating the occurrence of size differences among neighboring trees. In particular, general declining patterns from positive to negative spatial autocorrelations in diameters and biomass, except for plots with the heterogeneous stand structures, were noted at plots treated with high levels of fertilizer. This suggests that high fertilization may have influenced the realizations of microsite effects in the early stage of stand development. General trends in spatial autocorrelations between the two neighborhood structures considered were mostly similar except for several plots differing in intensities of spatial autocorrelations over the rotation.

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1. Introduction

Spatial arrangements of individual trees are often spatially autocorrelated, exhibiting aggregated patterns of similarities or dissimilarities in sizes (Liu and Burkhart, 1994; Fortin et al., 2002; Bullock and Burkhart, 2005). Growth and development of trees in a forest is complex and affected by various factors such as age, size, micro-environment, genetic backgrounds, and competition (Burkhart and Tomé, 2012). Among these factors, if effects of micro-environment and genetic backgrounds are assumed to be dominant, patches of trees with size similarities would be seen in a forest (Reed and Burkhart, 1985; Magnussen, 1994). In other words, positive spatial autocorrelation, a phenomenon which observations of a particular spatial object close in proximity are themselves correlated exhibiting similar characteristics (Fortin

and Dale, 2005), would be exhibited. On the contrary, if competitive effects among trees in proximity are expected to be prevalent, negative spatial autocorrelation, the opposite phenomenon to positive spatial autocorrelation, would be seen (Magnussen, 1994; Fox et al., 2007).

In an even-aged forest stand, the degree of change in interdependence among individual trees is expected to vary in relation to the developmental stage of that forest stand, and a hypothesis on the temporal change in inter-dependence of trees is suggested as follows. During the early stage of stand development before which an individual tree starts to compete with neighboring trees, tree growth would be largely influenced by the local microenvironment (Gray and Spies, 1997; Li and Yang, 2004) and genetic characteristics (Waxler and Van Buijtenen, 1981), generating spatially observable patterns similar in size and growth capacity. As a result, positive spatial autocorrelation would be expected and represented. As a forest stand shifts into the stage of competition, dissimilarities in size and growth potential among neighboring

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trees may occur (Hühn and Langner, 1995). Superior trees would out-compete neighboring trees resulting in size differences among trees. As a consequence, negative spatial autocorrelation would be exhibited. Inferior trees would die out due to intense competition, and dominant and co-dominant trees would remain. As conditions in the forest stand stabilize and favorable environments for micro-site variability reform, the surviving trees will develop with a constant relative growth rate, which again will give rise to positive spatial autocorrelation among neighboring trees in a forest stand (Reed and Burkhart, 1985; Magnussen, 1994; Fox et al., 2007; Suzuki et al., 2008).

A number of studies have been conducted to characterize temporal changes of spatial autocorrelation in forest stands. Among the investigated species are larch, jack pine, loblolly pine, and Eucalyptus. For larch (ages 11–50; Hühn and Langner, 1995) and jack pine (ages 15–56; Kenkel et al., 1997), spatial autocorrelations from middle to later ages were examined. They both found positive spatial autocorrelation for diameters at earlier ages, however, at the later stages of stand development, positive spatial autocorrelation for jack pine was shown, whereas negative spatial autocorrelation for larch was detected. In loblolly pine spacing trials, Liu and Burkhart (1994) found that spatial autocorrelation of detrended diameters decreased from positive to negative in trials with closer spacings (ages 1–9); Bullock and Burkhart (2005) found an increase in the proportion of plots with significant spatial autocorrelation of detrended diameters with planting densities and time (ages 2–11), where the trend peaked and then declined. In loblolly pine dominant stands, Reed and Burkhart (1985) found a curvilinear trend of spatial autocorrelation of basal area over time. Fox et al. (2007) showed change in spatial autocorrelation over nearly thirty years of measurements in thinning trials of Eucalyptus. In their study, there was a decreasing trend of positive to negative spatial autocorrelations from the early to later ages for diameter, with some plots remaining consistent or showing a slight increase after the minimum was reached. However, studies related to temporal variations of spatial autocorrelation in forest stands differ in tree species, investigated time frame, and site conditions. Moreover, there is still a lack of information on how spatial autocorrelation would change according to treatments applied in a forest stand over time.

The objective of this study was to characterize the change in spatial autocorrelations of even-aged clonal and seed-origin Eucalyptus plantations in Brazil over the rotation, where differing levels of fertilization, irrigation, and stand structure treatments were applied. Two neighborhood structures differing in numbers of trees accounted for in the neighborhood matrix were also investigated to look at the degree of change in spatial autocorrelation. In addition, tree growth in relation to spatial autocorrelation was discussed.

2. Materials

2.1. Study site

The data used in this study come from the Veracel Celulose (VER; a pulp and paper company) site located in Eunapolis, Bahia in Brazil (16°21′S, 39°34′W), which is part of the Brazil Eucalyptus Potential Productivity (BEEP) project sites (Fig. 1). The BEEP project was initiated in 2001 to examine the effects of intensive fertilizer applications and water supply on the growth potential of clonal Eucalyptus. The project was installed at eight different geographical locations in Brazil, and growth content and productivity were investigated (see Stape et al. (2010) for more details about the project). The VER site is located at an elevation of 187 m and on Ultisols (a depth of 0–40 cm). Mean annual temperature over the
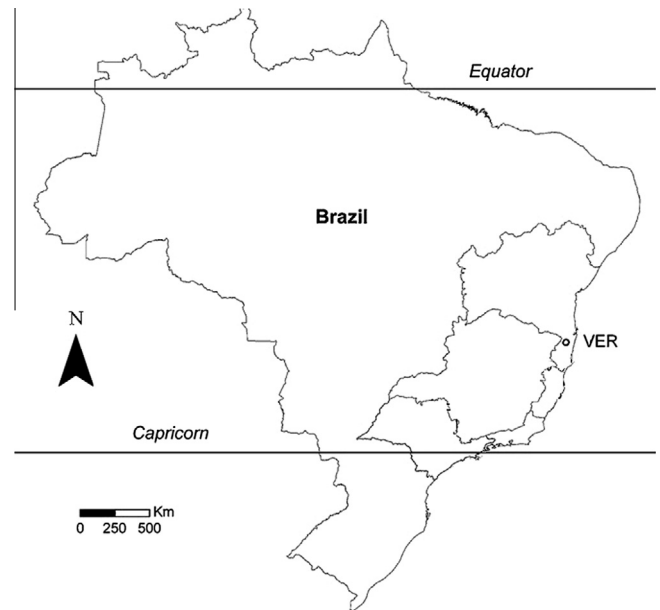

Fig. 1. Location of study site (adapted from Stape et al., 2010).

study was 23.0 °C; 21.3 °C in dry and 24.5 °C in wet seasons, respectively. Annual precipitation averaged 1433 mm; 888 mm in wet and 545 mm in dry seasons each. The wet season was considered to be from October to March, and the dry season was between April and September. The research site was originally grassland. The planting date was March 2001, and a clonal sapling selected by the participating company was planted. A seed-origin sapling was also planted (Stape et al., 2010).

2.2. Experimental design

Fertilization, irrigation, and stand structure adjustments were applied and evaluated. In clonal plots, high and traditional levels of fertilization (Table 1), and irrigated (additional 846 mm/year) and non-irrigated treatments were compared, while incorporating two different forms of stand structure, in which one is uniform and the other is heterogeneous (see Stape et al. (2010) for additional details on trial establishment). The main difference between the two structures was planting dates. The uniform stand structure was created by planting trees in a single day, whereas trees were planted on three different days in the heterogeneous stand structure; one-third of the trees were planted on day 0, day 40, and day 80, respectively. Planting locations were arbitrarily selected within a row at each day of planting. Heterogeneous stand structure is also termed as staggered planting due to the three different time points of tree planting within a plot. The heterogeneous stand structure was proposed to resemble the structure of seed-origin plots, which has a wide array of trees with different size classes. In seed-origin plots, the same treatments as the heterogeneous stand structure were applied. Abbreviations used in this paper for each treatment are presented in Table 2.

A total of 40 plots were established at the VER site. Among them, eight plots were established as extra plots for destructive samplings to construct biomass equations. Thus, 32 plots were used in this analysis. Each plot was assigned a treatment, and four replicates were established. The plot size was 30 m × 30 m with two buffer rows surrounding 36 trees planted (6 rows × 6 columns) for measurements. Intervals between trees for both rows and columns were approximately 3 m (1111 trees per hectare). Weed control was conducted continuously (Stape et al., 2010).