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Effects of tillage intensities on spatial soil variability and site-specific management in early growth of *Eucalyptus grandis*

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ABSTRACT

Soil tillage is one of the most common and important site preparation managements in forestry. However, in highly variable soils, uniform management practices might not be the best alternative. Site-specific management on the other hand, allows an optimal resource management as well as decreased environmental impact. However, the choice of a suitable strategy to manage areas with high soil variability is still a challenge. Our goal was to compare strategies that use soil characteristics to improve the comparison of tillage managements on *Eucalyptus grandis* growth. Specifically, we aimed to: compare strategies that incorporate soil characteristics into the models to compare tillage treatments; to determine the most useful soil characteristics for zone management delineation; and to compare tillage methods for site-specific management. We compared tillage intensities in contrasting soil types in a randomized complete block design with four and five replications. Tillage treatments included pit-planting, disc harrowing, and subsoiler. Experimental units consisted of three rows of fifteen trees each. Soil characteristics as well as plant height and diameter were evaluated periodically during the first 30 month after implantation. Intra-plot variability was described with multivariate geostatistical models. Using soil properties as covariates in the model to compare tillage treatments improved model fit. When root development is limited by soil conditions and electroconductivity is high, tillage intensity makes a difference in plant growth; subsoiler is the best treatment when electroconductivity is high, while disc harrowing is the best when electroconductivity is low. However, when root development is not limited by soil conditions, no differences were found between subsoiler and disc harrowing. We show how the use of soil characterization is a tool that provides better comparisons among treatments when high intra-plot variability is present. Additionally, the use of soil characterization either directly into the model or to determine zones provides useful information for site-specific management. Site-specific management could therefore easily be implemented to decrease the environmental impact of soil tillage as well as to increase wood production in forestry.

1. Introduction

The *Eucalyptus* genus has more than 500 species used for afforestation and is the single most important genus in terms of rapid-growth species (Flynn, 2005). Specifically, *Eucalyptus grandis* is one of the species with the largest area of afforestation having a sustained area expansion since the 1990s (Gonçálvez et al., 2004). Afforestation is generally established in low fertility or degraded soils and therefore, a general consensus exists in the literature about tillage benefits. Tillage is beneficial for weed control (McLaughlin et al., 2000; Wetzel and Burgess, 2001; Villalba et al., 2010), and improving soil physical conditions for root (Smith, 1998) and plant growth (Worrell and Hampson, 1997; Querejeta et al., 2001). On the other hand, it is not well established whether low or high intensity tillage systems are more beneficial. The reports regarding the effect of tillage intensities on tree growth parameters are not consistent and may be site-specific (Carnerio et al., 2008; Graham et al., 2009).

Tillage systems used for forest plantations range from intensive tillage such as subsoilers (Schönau et al., 1981) to reduced tillage systems such as disking (Norris and Stuart, 1994; Madeira et al., 1999; Du Toit, 2008). Some studies found a benefit of tillage systems when compared to no-till systems, but no improvement in increasing tillage intensity (Morris and Lowery, 1988; Madeira et al., 1999; Lowery and Gjerstad, 1991; Garcia Préchac et al., 2001). However other studies found a clear advantage on more intense tillage systems such as subsoilers (Schönau et al., 1981;

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Gatto et al., 2003). Specifically, Smith et al., 2005 indicated that the improvements of subsoiler were strongly affected by soil type, soil condition, and soil water content at the time of site preparation. On the other hand, the most intensive tillage system such as subsoiler increases the amount of bare soil until canopy closure and therefore increases soil erosion risk (Worrell and Hampson, 1997; Baptista and Levien, 2010). Therefore, it is necessary to establish soil tillage systems with high production levels for each soil condition, while minimizing negative environmental impacts (Binkley et al., 2004; du Toit and Dovey, 2005).

Furthermore, experimental designs for studying tillage intensity are generally underpowered due to the requirement of large experimental units to capture treatment effects with the consequence of having experimental units with large heterogeneity within (Joyce et al., 2002; Zas, 2006). Appropriately capturing local heterogeneity in experimental design is challenging. The most widely used experimental designs for studying tillage effect are randomized complete blocks. With this design, local heterogeneity might not be properly captured (Grondona et al., 1996) due to non-linear patterns found in soil heterogeneity (Cressie, 1993). Furthermore, since large experimental units are required in tillage experiments of forest species in order to properly evaluate the treatment effects, an unintended increase of experimental unit variability occurs. Additionally, when abrupt changes in soil type and unevenness of terrain are present, poor estimation of treatment effects is obtained (Dutkowski et al., 2002). One alternative to characterize soil heterogeneity is the use of soil electroconductivity and soil properties (Rhoades et al., 1999; Corwin and Lesch, 2003). Soil electroconductivity and other soil properties have been used in classic geostatistical models for variogram construction and kriging prediction (Matern, 1960; Ripley, 1981; Diggle, 1988), to model the residuals error variance–covariance structure in mixed models (Gleeson and Cullis, 1987; Cullis and McGilchrist, 1990; Cullis et al., 1991; Smith et al., 2005), and for curve smoothing (Hutchinson y Gessler, 1994). Another alternative is to use soil properties to delineate management zones through cluster analysis (Yan et al., 2007) and to evaluate treatments within zones. Soil properties such as fertility, electroconductivity, organic matter, and texture, satellite images, topographic factors, as well as yield monitor maps have successfully been used for zone delimitation and management in agriculture (Franzen et al., 2002; Schepers et al., 2000, 2004). Therefore, spatial information from soil properties could be used in experiments to model within experimental unit heterogeneity. However, the best way to incorporate spatial variability into the models is not clear.

Precision forestry is therefore one of the tools that could be successfully used to determine optimal site-specific management (van Schilfgaarde, 1999). However, it is not evident which models would better capture the spatial variability. The goal of this study was to compare statistical tools that incorporate soil properties into the analysis of forest experiments with large intra-plot variability to control soil spatial heterogeneity. Specifically, we compared different strategies to incorporate soil characteristics to improve treatment estimation efficiency in forest experiments with large experimental units. We proposed a method to identify the most useful variables for zone delimitation to be used in site-specific management, and we evaluated the use of zone management for tillage intensities in forest experiments.

2. Materials and methods

2.1. Site description and experimental design

The experimental site was located in ‘‘Mellizos’’, Rio Negro Department, Uruguay (32°37′49″S; 57°10′07″W). Uruguay has a temperate climate with four clearly distinguished seasons and an isohydric precipitation regime. Yearly mean average temperature is 17.9 °C with a minimum average temperature of 12.2 °C and a maximum average temperature of 23.8 °C (Fig. 1). Average annual precipitation is 1200 mm and air relative humidity is 73%. The experiment was established in two contrasting soil types separated 500 m approximately (E_1 and E_2, Fig. 2). Dominant soils are Lithic Dystrudepts in one experiment (E_1) and Typic Argiudoll in the other experiment (E_2) (Table 1). The *E. grandis* commercial clone *X2334* was used. Both experiments were planted on April 4, 2011. The previous land use at the experimental site was native grasses. Disc harrowing and subsoiler were applied on January 14 and February 10, 2011, on E_1 and E_2 respectively. Pits were prepared for plantation on March 23, 2011.

A randomized complete block experimental design with three tillage intensity treatments was used. Tillage treatments were: pit-planting (P), subsoiler on the planting row (F), and disc harrowing on the planting row (R). Subsoiler was chosen as one of the treatments because it is used for forestry producers when soils have potential physical limitations for tree roots growth, yet it is

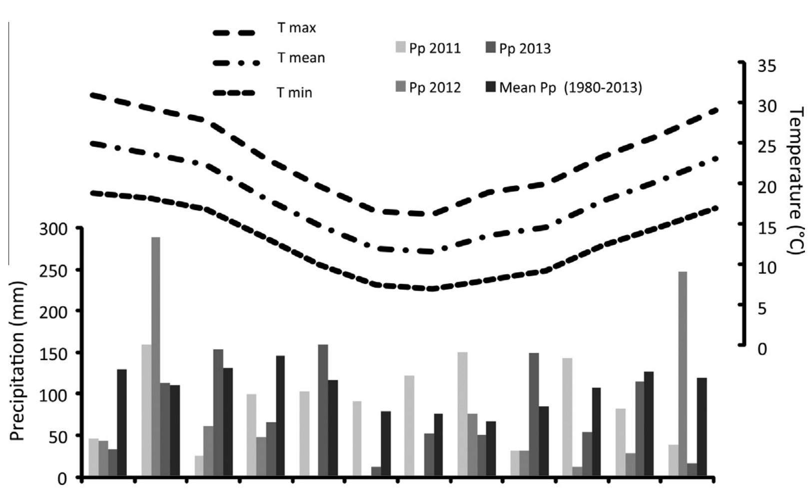

Fig. 1. Environmental conditions during the experimental growing seasons. Monthly accumulated precipitation for all years (Pp 2011, Pp 2012, Pp 2013), historical average accumulated precipitation (Pp from 1980 to 2013) and average minimum, mean and maximum temperature (Tmin, Tmean, Tmax).