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Eucalyptus and *Pinus* stand density effects on soil carbon sequestration

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ABSTRACT

Although afforestation of pasture and agricultural systems can increase C sequestration in soils, studies have shown wide variation in the magnitude, timing and direction of soil organic C (SOC) dynamics, depending on site conditions, management practices, and previous land use. Effects of stocking density on SOC have yet to be elucidated, however. The objectives proposed for this work were to quantify: (i) SOC content and distribution for the top 30 cm of the A horizon under native pasture compared with that following 8 years of afforestation (*Eucalyptus grandis* and *Pinus taeda* planted at different densities); (ii) SOC accumulation in the AB and the top of Bt horizons in afforested soils; and (iii) the contribution of the new vegetation (*Eucalyptus* and *Pinus*) to SOC. A field trial with three stand-densities of *E. grandis* and *P. taeda* and corresponding native pasture was established and soil samples were collected and assayed for five layers of the A horizon (0–5, 5–10, 10–15, 15–20, 20–30 cm), and the AB and Bt_1 horizons. Soil organic C concentration and $\delta^{13}C$ were determined, and the total SOC stock and C derived from the *Eucalyptus* and *Pinus* vegetation (young C) were calculated. Our results suggest that there was likely no significant change in SOC stocks in response to 8 years of afforestation with either *Eucalyptus* or *Pinus*. No significant differences in SOC stocks in the upper 30 cm soil layer as a whole were found among pasture, *Eucalyptus*, and *Pinus* treatments. By contrast, SOC in the AB and Bt_1 horizons was significantly higher under afforested sites than native pasture ($P < 0.001$ and $P < 0.039$, respectively). Soil $\delta^{13}C$ in the afforested treatments (0–30 cm) reflects the contribution of the new vegetation (*Eucalyptus* or *Pinus*) to SOC. Net accumulation of new SOC from the planted trees in the top 15 cm soil layer was equivalent to 0.20 Mg C ha^{-1} yr^{-1} for *Eucalyptus* and 0.30 Mg C ha^{-1} yr^{-1} for *Pinus*. Assuming initial declines in SOC following afforestation have largely ended and young C sequestration rates continue at the same rate, SOC stocks in the top 15 cm layer would reach those found under pasture after 15 and 11 years for *Eucalyptus* and *Pinus* plantations, respectively. Measurements of additional sites afforested with *Eucalyptus* and *Pinus* of different ages are needed to draw firm conclusions about the net SOC balance in these afforested pasture soils.

1. Introduction

Carbon sequestration in forest systems is generally high and the net C balance positive (IPCC, 2000; Lal, 2005). Although afforestation of pasture and agricultural systems can increase soil C sequestration, studies have shown wide variation in magnitude, timing and direction of soil C dynamics, depending on site conditions, management practices, and previous land use (Laganiere et al., 2010).

Soil C pools are generally greater under pasture systems than under row crop agriculture, and can decline for a period following afforestation as a consequence of tillage during site preparation (Paul et al., 2002). Short-term C dynamics following afforestation are therefore not necessarily indicative of longer-term trends. They found substantial variation in soil organic carbon (SOC) content following afforestation (0–30 cm depth), depending on plantation age, with SOC accumulating in the longer term (20–50 years). Soils of Uruguay show different patterns of SOC distribution with depth following afforestation compared to native pasture (Hernández and Salvo, 2006). While the balance of fine root and litter deposition and decomposition can result in SOM accumulation at the soil surface in afforested soils, SOC accumulation at the top of the Bt

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horizon over and above that typical of native pasture has also been found (Delgado et al., 2006). Dieste (1999) reported that the SOC was 9 kg m^{-2} (100 cm depth, A and Bt horizons) under grassland, and 11 kg m^{-2} (100 cm depth, A and B horizons) following afforestation of grassland with *Pinus taeda* and *Eucalyptus grandis* (15 years-old). By contrast, Céspedes (2007) reported lower SOC stocks in afforested grassland soils planted with *E. grandis* (25 years-old) compared to similar soils under pasture (A and Bt horizon, 45 cm depth in average). Effects of management factors on SOC following afforestation are not well known. For example, forest stands are planted at varying densities, depending on whether the management objective is pulpwood or sawtimber production. In Uruguay, *Eucalyptus* (principally *E. grandis*) is planted for pulp or sawtimber production whereas loblolly pine (*P. taeda*) is planted for sawtimber production. Management objective also affects stand rotation age, with plantations managed for pulp production typically harvested on an 8–10-year rotation whereas those managed for sawtimber are typically harvested on a 20-year rotation. Effects of planting density and rotation length on soil C following afforestation are not known.

The ^{13}C natural abundance isotope technique, based on the discrimination of ^{13}C and ^{12}C by plants during photosynthesis, can be used to better understand SOC dynamics (Smith and Epstein, 1971; Boutton, 1996). On average, plants with a C3 photosynthetic cycle have lower $^{13}C/^{12}C$ ratios in their tissues than do C4 plants (expressed as $\delta^{13}C$ values, $\sim-27‰$ for C3 species and $\sim-12‰$ for C4 species). Because SOC generally has a $\delta^{13}C$ value close to that of the vegetation from which it's derived, a change in vegetation (C3 → C4, or C4 → C3) can gradually shift soil $\delta^{13}C$ toward values inherent to the new vegetation. This isotope technique therefore allows the origin of C input to soil from the new vegetation to be estimated (Andreux et al., 1990). Uruguayan native pastures are mixtures of C3 and C4 grass species (Cayssials, 2010), whereas *Eucalyptus* and *Pinus* have a C3 photosynthetic cycle. The ^{13}C technique was used in a preliminary study to estimate the contribution of forest vegetation to SOC following afforestation of a degraded soil (Hernández and Salvo, 2006).

The objectives proposed for this work were (i) quantify and compare SOC content and distribution at the top of A horizon (0–30 cm) under native pasture with that following 8 years of afforestation (*E. grandis* and *P. taeda* planted at different densities); (ii) determine SOC accumulation in the AB and the top of Bt horizon in afforested soil use; and (iii) estimate the contribution of the new vegetation (*Eucalyptus* and *Pinus*) to SOC.

2. Materials and methods

2.1. Study site

The site for the stand spacing-density study was located at Los Moros Farm (Route 5, km 451, Rivera Department, Uruguay, Coordinates: 31°23′55.11″S and 55°41′43.88″W). At this site, an experiment with varying densities of *Eucalyptus* and *Pinus* plantations was established on native vegetation (native pasture without fertilizer added) in 2004. The site therefore allowed effects of three vegetation types on soil properties to be compared.

The climate of the region is temperate, with an annual mean temperature of 18.1 °C. The highest mean temperatures occur in January (24.1 °C), and the lowest in June and July (12.3 °C). Changes in temperature are frequent and pronounced throughout the year. The region is dominated by sedimentary rocks from the Tertiary Era, represented by fine and very fine sandstones (MIEM, 2015) with a landscape consisting of low plateau hills. The native vegetation of the region is dominated by perennial warm season grasses (with a C4 photosynthetic cycle) (*Axonopus* spp., *Schizachyrium* spp., *Paspalum* spp., *Chloris* spp., *Andropogon* spp., *Eragrostis* spp. and *Aristida* spp.) and secondary cool season grasses (*Briza* spp. and *Piptochaetium* spp.).

The dominant soils of the field trial are Coarse-loamy, siliceous, active, thermic Humic Hapludults (Soil Survey Staff, 2014), Albic Alisols in the FAO soil classification system, (IUss, 2007). Table 1 presents characteristics corresponding to the A, AB and the upper part of B horizon (Bt_1) from nine profiles at the experimental site.

2.2. Species-density field trial

The species-density field trial combines two tree species (*E. grandis* Hill ex Maiden and *P. taeda* L.) and three initial planting densities, 816, 1111 and 2066 seedlings ha^{-1}. At the time of sampling the trees were 8 years old and the effective densities resulting from natural thinning were 711, 996 and 1578 trees ha^{-1} for *E. grandis*, and 782, 1070 and 1911 trees ha^{-1} for *P. taeda*. These treatments were compared with native pasture (grasses) in the area surrounding the experiment. Three replications of each tree species and density combination were compared with three replications for the native pasture adjacent to each plot at the experimental site.

2.3. Soil sampling and SOC determination

A stratified randomized soil sampling was performed in the experimental plots and adjacent native pasture. Following careful removal of the O horizon (litter layer), composite samples (twenty soil cores) for each replication of the treatments (forest soil and pasture soil) were taken at five soil depths from the top of the A horizon: 0–5, 5–10, 10–15, 15–20, and 20–30 cm. For the AB horizon (from 48 to 66 cm depth) and the top of the Bt horizon (Bt_1, from 66 to 90 cm depth), composited soil samples of native pasture, *Eucalyptus* and *Pinus* (across all the densities for *Eucalyptus* and *Pinus*) were taken. Three samples per plot from each depth were also collected for bulk density determination (with a cylinder of known volume). For SOC determination, soil samples were dried at 40 °C and crushed to <100 mesh. Samples for bulk density were saturated 24 h with water, dried to 105 °C for 48 h, and weighed (García-Préchac and Kaplán, 1974).

The SOC and $^{13}C/^{12}C$ was determined using an Elemental Analyzer Flash EA 112 coupled to a mass spectrometer Finnigan MAT DELTAplus XL (Bremen, Germany). Analytical precision for C and $\delta^{13}C$ values were 0.2% and 0.1‰, respectively. The relative abundance in ^{13}C is expressed in $\delta^{13}C$ values, according to:

$$\delta^{13}C = 1000 * \left(^{13}C/^{12}C - {}^{13}C/^{12}C_{PDB}\right)/^{13}C/^{12}C_{PDB} \quad (1)$$

where $^{13}C/^{12}C$ is the isotope ratio for the sample, and $^{13}C/^{12}C_{PDB}$ is the standard value (Pee Dee Belemnite). We calculated the C input from the new vegetation (*Eucalyptus* or *Pinus*) as follows:

$$\alpha(\%) = 100(\delta - \delta_0)/(\delta_1 - \delta_0) \quad (2)$$

where α is the ratio of young (i.e., from the new vegetation) C (*Eucalyptus* or *Pinus*) to total C, expressed as a percentage, δ is the $\delta^{13}C$ of SOC at $t = 1$, δ_0 is the $\delta^{13}C$ of SOC at $t = 0$, and δ_1 is $\delta^{13}C$ of the new vegetation residues. Here, δ was the $\delta^{13}C$ of SOC under each treatment (*Eucalyptus* or *Pinus*); δ_0 was the $\delta^{13}C$ of SOC under native pasture; δ_1 was the $\delta^{13}C$ from *Eucalyptus* and *Pinus* vegetation. We assumed that the principal contribution to SOC of the 0–5 cm layer is litter decomposition products ($-29.0‰$ and $-29.4‰$ for *Eucalyptus* and *Pinus*, respectively), and the principal contribution to SOC of the 5–30 cm layer is root turnover (Hernández et al., 2014). There are no available data for $\delta^{13}C$ from roots, so we assumed values were similar to $\delta^{13}C$ from wood ($-27.1‰$ and $-28.0‰$ for *Eucalyptus* and *Pinus*, respectively).