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Eucalyptus plantation effects on soil carbon after 20 years and three rotations in Brazil

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ABSTRACT

How will shifting land use from row crops and pasture to intensively managed forests alter soil carbon storage? Demand and profitability has led to a dramatic increase in *Eucalyptus* production with a total planted area over 20 million hectares worldwide. The impacts of these short-rotation (6- to 8-year harvest cycle) *Eucalyptus* plantations on soil carbon appear to be variable, and the available case studies are typically too short term to support generalization. Spatial heterogeneity of soils across landscapes requires repeated sampling for reliable documentation of soil carbon changes over multiple rotations. We characterized soil carbon stocks and change over two decades in 306 operational *Eucalyptus* plantations across a 1200-km gradient. Across all sites, soil C (0–30 cm depth) in 2010 averaged 29 Mg ha^{-1} (± 0.70 Mg ha^{-1}), tending to increase with increasing soil clay content, precipitation, and mean annual temperature. Average soil C from the original sampling to 2010 (ranging from 18 to 26 years or approximately 3 to 4 rotations) showed a slight decrease (−0.22 ± 0.05 Mg ha^{-1} yr^{-1}, $P < 0.0001$). Tropical sites in Region 1 (Bahia state) showed no net change (−0.11 Mg ha^{-1} yr^{-1}, $P = 0.1874$, whereas tropical and subtropical sites in Region 2 (Espirito Santo state) lost soil carbon stocks (−0.87 Mg ha^{-1} yr^{-1}, $P < 0.0001$), and subtropical sites in Region 3 (São Paulo state) also remained the same (0.06 Mg ha^{-1} yr^{-1}, $P = 0.3969$). Soil carbon change tended to increase with precipitation during the dry season, and had weaker associations with soil order and mean annual temperature.

1. Introduction

Demands for wood products have led to the adoption of silvicultural systems for managing high-yielding monoculture forest plantations in the tropics and subtropics. Species of *Eucalyptus* account for a large portion of these plantations with approximately 20 million hectares (ha) worldwide (Iglesias-Trabado and Wilstermann, 2008) and 4.75 million ha in Brazil (ABRAF, 2011). *Eucalyptus* plantations have historically provided pulpwood, charcoal, and firewood, and have begun expanding into the solid wood products. The impacts of this widespread land-use practice on soil C are important for both sustaining forest productivity, and accounting for potential climate influences.

Ensuring continued productivity of plantations is important to land-holding forestry companies that are invested in maintaining the supply of pulpwood to their production chain. In the tropics, where soils are typically weathered from the warm, humid climate, the protection and enhancement of soil organic matter may aid in maintaining site productivity and therefore the sustainability of operations (Zinn et al., 2002).

Tropical forest plantations are often located in highly weathered clays with low cation exchange capacity (CEC). Any change in the C stock of tropical soils could be important in relation to: providing a source and sink for plant nutrients, increasing CEC, promoting soil aggregation and increasing infiltration thereby lowering runoff, improving water holding capacity, increasing microbial activity, and buffering pH with weak acid groups (Lal, 2004). Soil carbon has been shown to increase or stay the same in other *Eucalyptus* plantations in the top 10 cm, but maintaining or

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increasing quantities of soil C has been shown to have variable effects on soil chemical properties (N, P, K, Ca, Mg, pH; Nambiar and Harwood, 2014). Additionally, compared to gross primary production rates and the annual input of C to the belowground portion of the ecosystem, soil carbon stocks and rates of change may be small in comparison (Ryan et al., 2010).

Soil carbon changes following forest establishment often vary with land-use history and soil properties (de Koning et al., 2003; Don et al., 2010; Laganiére et al., 2010). Long-term soil experiments are challenging to sustain due to the organization and collaboration required between researchers and land-owners, and the short term nature of funding and land tenure (Richter et al., 2007). However, long-term monitoring of individual sites is more reliable than chronosequence studies (Laganiére et al., 2010; Binkley and Fisher, 2013), and many sites are required to gauge the changes that develop across a suite of geographic gradients that influence soil change. Landscape-scale issues in soil C need to be sampled at spatial and temporal scales relevant to the scale of land-management, with careful quality assurance protocols (Paul et al., 2002).

We characterized soil C stocks across 306 *Eucalyptus* plantations along a 1200-km gradient in Eastern Brazil, and followed changes that resulted from over 20 years of operational silviculture. Our objectives were to (1) quantify mineral soil carbon stocks and change over time and (2) examine relationships of soil C and change in soil C with clay content, mean annual temperature, wet and dry seasonal precipitation, soil order, and region.

2. Materials and methods

This research project was designed for sufficient spatial and temporal scale analysis to determine patterns in soil carbon stocks across the region, and changes in soil carbon over time based on repeated sampling and soil archives (Richter et al., 1999).

2.1. Site descriptions

Field sites were located in three regions in Brazil ranging from tropical to subtropical climate (and corresponded to three companies): Region 1 (Bahia, Bahia Pulp/Copener), Region 2 (Espirito Santo and southern Bahia, Fibria), and Region 3 (Sao Paulo, Suzano Pulp and Paper) (Fig. 1). We sampled 110 plantations in each region, for a total of 330 original sampling points. *Eucalyptus* plantations continued through the final sampling in 2010 at 306 of the sites (107 in Region 1, 98 in Region 2, and 101 sites in Region 3).

Sites range in elevation from 8 to 1000 m above sea level, with mean annual rainfall of 800 to 2000 mm and mean annual temperature of 16 to 24 °C (summarized based on the FAO Worldclim database, Hijmans et al., 2005). Three soil orders, Entisols, Oxisols, and Ultisols (U.S. taxonomic system) or Arenosols, Ferralsols, and Alisols (IUSS Working Group, 2014) were represented in each region with proportions of each according to predominance in operational plantations (Table 1).

All sites would have supported Atlantic Forest vegetation prior to European settlement. Current plantations of *Eucalyptus* followed decades of agricultural crop production and pastures, however information was not available pertaining to exact prior land-use history. Initial conversion to agricultural production likely included substantial losses of soil, carbon, and nutrients (Detwiler, 1986). Widespread *Eucalyptus* plantations developed in the mid-1980s and have been in continuous production since establishment. Prior to the year 2000, typical silvicultural practices included intensive site preparation, burning of slash, harrowing/bedding of soil, and minimal fertilization. Recent practices include the elimination of burning, minimal cultivation (with retained slash), and intensive fertilization. Fertilization practices varied over time and across sites, and has not been shown to alter changes in soil C (Ryan et al., 2010). Typical rates of fertilization in *Eucalyptus* plantations in Brazil include additions of 80 kg ha^{-1} of N, 50 kg ha^{-1} of P, 130 kg ha^{-1} of K, and 450 kg ha^{-1} of Ca (Binkley and Fisher, 2013, Fig. 14.7). Genetic selection shifted from seed-origin seedlings to clonal propagation. Hybrids used in these plantations are primarily *Eucalyptus grandis* × *urophylla* in Regions 1 and 2, and *Eucalyptus grandis* in Region 3.

2.2. Experimental design and soil sampling

Soils were first collected from 1984 to 1993 by horizon from one soil pit in each of the selected operational *Eucalyptus* plantations as part of a soil survey (Region 1: Kreijci, 1985/91; Region 2: EMBRAPA, 2000; Region 3: Rizzo 1984/86). The O horizon was not included in the original soil sampling as the establishment of the plantations generally included incorporation of any organic materials into the A horizon. Subsequent harvesting and site preparation treatments also tended to mix organic material into the A horizon, so any long-term contribution of the O horizon to overall soil C would be largely found in the mineral soil. Within a single rotation the average rate of C accumulation in O horizons is small, about 500 kg ha^{-1} yr^{-1} (Ryan et al., 2010).

Each site was resampled in 2001 and 2010 within 5–20 m of the original soil pit with 5–7.6 cm diameter bucket augers, using a composite sample approach. The advantage of sampling deep soils for so many sites as in the original soil sampling was outweighed by the greater confidence of having more subsamples but to a 30 cm depth. We expect that soil C dynamics are more pronounced in the upper most soil, but we note that extensive rooting by *Eucalyptus* trees adds C to depths greater than 10 m (Laclau et al., 2013). Samples were collected at two depths: 0–15 cm and 15–30 cm. Three subsamples were collected at three sampling points (i.e. nine samples per plot): within the planting row, halfway between the planting rows, and halfway between those sampling points. All nine points were composited in the field for each depth. Preliminary analysis at similar sites indicated nine sub-samples were similar within sites (data not shown). Bulk density was collected with volumetric rings at the three sampling points from within the 0–15 cm and 15–30 cm depths and composited in the field. Ring volumes in 2010 were 91.8 cm^3 for Region 1, 80.7 cm^3 for Region 2, and 86.7 cm^3 for Region 3. The same volumetric rings were used in 2001 and 2010 for Regions 1 and 2, however information for sampling ring volume for 2001 in Region 3 was not found. Preliminary analysis of subsamples of bulk density in Region 1 and Region 2 showed no significant differences among subsampling locations within a plot (data not shown). Permanent stone markers, stand maps, and GPS coordinates mark sampling locations for future resampling.

2.3. Data conversions and laboratory analysis

Soil organic matter (SOM) by horizon from the original sampling was translated to 0–15 cm and 15–30 cm increments by weighting SOM values based on what fraction of the 0–15 or 15–30 cm depth they consisted. For instance, if horizons were 0–20 cm and 20–80 cm, the weight for translating from 0–20 to 0–15 would be 1.00. For the translation to the 15–30 cm horizon, 0.20 × %SOM would be taken from the 0–20 cm horizon and added to 0.80 × %SOM from the 20–80 cm horizon. By this means, we estimated what the %SOM would have been if it had been sampled from 0–15 and 15–30 instead of by horizon.

Soil samples from the original sampling period (1984–1993) were analyzed for SOM by the Walkley–Black method (Jackson, 1958). The only archived soil samples from the original soil survey