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Changes in soil carbon of pastures after afforestation with mixed species: Sampling, heterogeneity and surrogates

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ABSTRACT

Accurate and efficient estimation of soil C is vital to understanding and monitoring the role of afforestation in C sequestration. Here, we focused on the potential of mixed-species plantings, for which there is negligible information but expanding investment due to their added environmental benefits. We surveyed soil C and N over a representative chronosequence (5–29 years old) of existing plantings, including measurements in the adjacent pastures to account for differences in soil type and land-use history among properties. Vegetation characteristics of the tree plantings were measured to identify potential surrogates for rapid assessment of soil C. Soil C was highly heterogeneous under the plantings and the adjacent pastures, with up to eight cores required to sample adequately a plot of 400 m^2. Vegetation surrogates had limited success in predicting soil C after afforestation, with the only strong predictors being tree density and planting age. Three decades of afforestation with mixed species had not led to substantial changes in C concentration or content of the soil. The C:N ratio of soils increased with planting age suggesting that the C becomes more resistant to decomposition after afforestation. Over longer time scales, tree plantings are likely to have larger impacts on the amount and forms of soil C.

1. Introduction

Forests sequester substantial amounts of C, with an estimated 2.4 ± 0.4 Pg C yr^{-1} stored globally between 1990 and 2007. Globally, similar amounts of C are stored in the live biomass (363 ± 28 Pg C) and the soil beneath forests around the world (383 ± 30 Pg C, Pan et al., 2011). Afforestation of agricultural land provides an important opportunity to sequester atmospheric C and potentially mitigate climate change (IPCC, 2007). There is a pressing need to understand how different types of forests – single or mixed species, native or exotic species – affect storage of soil C. Little is known about the potential for native mixed-species plantings, which have the additional environmental benefits of improving species diversity (Felton et al., 2010) and habitat structure (Munro et al., 2009), to store soil C (e.g. Kasel et al., 2011). Accurate and efficient estimation of soil C is vital for understanding, monitoring and advocating the role of afforestation in sequestering atmospheric C in the soil.

The capacity of afforestation to increase soil C in agricultural landscapes is highly variable, and is dependent on edaphic (e.g. soil type), climatic (e.g. precipitation) and biotic (e.g. species choice) factors, as well as land-use history (Paul et al., 2002; Laganière et al., 2010). Our understanding of how soil C accumulates following afforestation is hindered partially by the design limitations of past studies. Most studies rely on single paired-site comparisons to infer temporal changes in soil C, rather than on repeated sampling (e.g. Poulton et al., 2003) or chronosequences (e.g. Ritter, 2007). Studies rarely account for productivity differences among sites (e.g. past management, soil type) that affect C sequestration potential of a planting. Where there are no established networks of long-term monitoring sites, surveying a chronosequence of paired planting-pasture sites is one option to overcome these issues. Furthermore, given the variation in soil C within a site (CV = 0.1–0.6, Wilson et al., 1997; CV = 0.1–0.6, Paz-Gonzalez et al., 2000), adequate sampling of different soil depths, of cores within plots and of plots across a site is required.

Afforestation has been promoted widely as an effective way to sequester C in the short-term while alternative energy sources are developed (IPCC, 2007). If afforestation is to be an effective tool for mitigating climate change, forests must be planted across large areas. Emerging carbon markets and tax systems suggest that 'carbon farming' is becoming a viable alternative farming practice (Larson et al., 2008). This will require accurate accounting of C storage at both the scale of individual farms and across landscapes, which is infeasible using traditional labour-intensive soil sampling. Potential approaches for improving the estimation of soil C include: (1) quantifying the sampling effort required for adequate estimates; and (2) identifying vegetation surrogates for soil C.

Here, we provide new knowledge on the effective measurement of soil C in a representative chronosequence (5–29 years)

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Table 1
Characteristics of the tree plantings surveyed. Soil type is based on Australian Soil Classification (ASC, Isbell, 2002). Litter mass is the mean of 20 quadrats per site.

Planting age (yr)	ASC	Latitude (°S)	Longitude (°E)	Precipitation (mm yr^{-1})	Mean annual max. temp. (°C)	Tree density (trees ha^{-1})	Basal area (m^2 ha^{-1})	Live basal area (%)	Litter mass (t ha^{-1})
5a	Va5	36.4581	145.7736	568	22.9	456	4.26	96.8	2.4 ± 1.4
5b	Ub24	36.6083	145.6178	594	21.6	1144	11.32	99.8	5.4 ± 4.2
21	Qc1	36.3894	145.9489	630	20.3	337	15.03	80.7	15.1 ± 6.5
22	Qc1	36.5266	145.7530	601	20.9	211	12.98	100.0	8.6 ± 7.4
28	Qc1	36.5266	145.7476	601	20.9	393	9.80	98.4	10.6 ± 4.5
29	Va10	36.1710	146.9502	705	22.2	582	39.80	96.2	16.8 ± 6.4

of mixed-species plantings dominated by eucalypts. Plantings on pastures in the low-medium rainfall zone (400–800 mm yr^{-1}) of temperate Australia were chosen because this land is most likely to be abandoned increasingly in favour of afforestation in the near future (Polglase et al., 2008). We took paired measurements of the adjacent pasture along this chronosequence to account for differences in soil type and land-use history among properties. Soil was collected from two soil depths, with multiple cores in each to determine the sampling effort required for the accurate measurement of soil C and its spatial heterogeneity within a plot. Characteristics of the vegetation (e.g. cover, size and mass) were measured to explore whether these provide potential surrogates for measuring soil C.

2. Materials and methods

2.1. Study area

We focused on tree plantings on grazing properties in northern Victorian, Australia. Prior to European settlement, the region was covered in woodlands (10–30 m tall, 10–30% projective foliage cover, Specht, 1981) dominated by *Eucalyptus* species with grassy understoreys. The region has been extensively cleared since European settlement in the 1840s for dryland agriculture, including cereal crops and pasture for stock. The climate across this region is temperate with seasonal changes in mean monthly maximum temperature (12.6–31.8 °C) and minimum temperature (3.1–15.2 °C), and a winter-dominant annual precipitation (670–715 mm yr^{-1}, BOM, 2009).

Six tree plantings were selected that covered the available range of ages (5–29 years) and that had a species mix that was representative of mixed-species plantings on pasture in the region (Table 1). The plantings were established by ripping the soil into furrows, fencing out stock grazing and hand planting tubestock seedlings into the furrows at 3 m spacings, with no subsequent management intervention. The sites were planted with a mixture of five to eight regionally endemic trees and shrubs from the genera *Acacia* Mill., *Allocasaurina* L.A.S. Johnson, *Callistemon* R. Br., *Dodonaea* Mill., *Eucalyptus* L'Hér and *Melaleuca* L., with only *E. albens* Benth. and *E. sideroxylon* A.Cunn. ex Woolls common to all six plantings. The soils at all plantings were hard neutral to alkaline yellow mottled sodosols with a sandy loam texture (Isbell, 2002).

2.2. Soil and vegetation survey

At each property, a tree planting and adjacent pasture site were surveyed between May and December 2010. The adjacent pastures, which continued to be grazed by stock and have fertilizer added, were sampled to determine differences in soil C between land uses, and to standardize for potential differences in soil characteristics and disturbance histories among the properties, thereby providing an often neglected point of reference. Measurements in the pasture site were used as an indicator of conditions at the planting site if it had not been established and not as an estimate of conditions prior to establishment. A single 400 m^2 plot was established within each planting and another in the adjacent pasture because we sought to determine variation and spatial patterns at the plot scale and not across the site. The pasture plot was located ca 50 m from the planting to limit the influence of the trees.

Soils were sampled from upper (0–5 cm) and lower (5–30 cm) soil layers, with ten separate samples collected for each depth. Soil samples were collected at random points, outside the rip lines to avoid obvious differences in soil structure, across the plot with a hand auger (diameter 4.2 cm). We considered this to be representative sampling of a planting because rip lines covered ≤10% of the area of a planting. Sampling was not stratified to categories such as row and inter-row because the influence of trees (canopy, roots, etc.) is likely to decline monotonically with distance. This influence of trees was quantified for each sample by the measures of cover and biomass outlined below. Sampling was not stratified according to tree species. Additional samples were taken from three sampling points for each depth to measure bulk density. These were collected by gently tapping a steel cylinder (96 cm^3) into the soil at the surface for upper soil samples and ca 20 cm depth for lower soil samples (Minoshima et al., 2007). All soil samples were placed into airtight plastic bags and immediately put on ice, and stored at 4 °C upon return to the laboratory.

Vegetation characteristics of the plantings were measured to determine if these could provide easily measured surrogates of soil C. Diameter at breast height (at 1.3 m) was measured for all trees and basal diameter (at 10 cm) was measured for all shrubs, due to the shrubs' multi-stemmed form, within the 400 m^2 plot. The species and status (live/dead) of all trees and shrubs was determined. Trees were considered to be dead when they had no live leaves in their crown (Cunningham et al., 2007). At each sampling point, digital photographs were taken of the ground cover within a 25 cm × 25 cm quadrat and of the canopy cover in the plantings only. Litter and live biomass, including grasses and herbs, were collected destructively within the quadrat. Litter was defined as any dead biomass that could be detached gently by hand whereas live biomass included any green plant material.

2.3. Sample processing, analysis and calculations

All soil samples were sieved to 2 mm and roots ≥1 mm diameter were removed by dry picking. Gravimetric moisture was determined after drying ca 20 g of moist soil at 105 °C for 48 h. The remainder of each sample was air dried and used in subsequent analyses of C and N content.

Soil pH was measured using a conductivity meter (WP-81 meter, TDS, Australia) in a 1:5 soil–water suspension. Composite samples (20 g composed of ca 4 g from 5 soil samples randomly chosen from the corresponding ten) were used to measure pH for each site × land use × depth combination. All soils were acidic (pH = 4.5–6.1) indicating the absence of inorganic C and no need for additional pre-processing of samples prior to CHN analysis (Slattery et al., 1999). Each soil sample was hand-mixed and a 5 g subsample was taken. All identifiable plant fragments were removed and the soil was ground to a fine powder using a mill. C and N concentration of each sample was determined from an accurately weighed subsample of 4–5 mg using catalytic combustion and thermal