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Previous land use and climate influence differences in soil organic carbon following reforestation of agricultural land with mixed-species plantings

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ABSTRACT

Reforestation of agricultural land with mixed-species environmental plantings (native trees and shrubs) can contribute to mitigation of climate change through sequestration of carbon. Although soil carbon sequestration following reforestation has been investigated at site- and regional-scales, there are few studies across regions where the impact of a broad range of site conditions and management practices can be assessed. We collated new and existing data on soil organic carbon (SOC, 0–30 cm depth, $N = 117$ sites) and litter ($N = 106$ sites) under mixed-species plantings and an agricultural pair or baseline across southern and eastern Australia. Sites covered a range of previous land uses, initial SOC stocks, climatic conditions and management types. Differences in total SOC stocks following reforestation were significant at 52% of sites, with a mean rate of increase of 0.57 ± 0.06 Mg C ha^{-1} y^{-1}. Increases were largely in the particulate fraction, which increased significantly at 46% of sites compared with increases at 27% of sites for the humus fraction. Although relative increase was highest in the particulate fraction, the humus fraction was the largest proportion of total SOC and so absolute differences in both fractions were similar. Accumulation rates of carbon in litter were 0.39 ± 0.02 Mg C ha^{-1} y^{-1}, increasing the total (soil + litter) annual rate of carbon sequestration by 68%. Previously-cropped sites accumulated more SOC than previously-grazed sites. The explained variance differed widely among empirical models of differences in SOC stocks following reforestation according to SOC fraction and depth for previously-grazed ($R^2 = 0.18$–0.51) and previously-cropped ($R^2 = 0.14$–0.60) sites. For previously-grazed sites, differences in SOC following reforestation were negatively related to total SOC in the pasture. By comparison, for previously-cropped sites, differences in SOC were positively related to mean annual rainfall. This improved broad-scale understanding of the magnitude and predictors of changes in stocks of soil and litter C following reforestation is valuable for the development of policy on carbon markets and the establishment of future mixed-species environmental plantings.

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1. Introduction

There is increasing interest in reforestation of agricultural lands to sequester carbon in woody biomass and potentially mitigate greenhouse gas emissions (e.g. Canadell and Raupach, 2008; Cunningham et al., 2015a). Reforestation can increase terrestrial carbon through humification and storage in soil organic carbon (SOC; Lal, 2005). While reforestation of agricultural lands significantly increases carbon sequestration in biomass compared with crop or pasture (e.g. Paul et al., 2008; Cunningham et al., 2015b), changes in SOC following reforestation are highly variable and uncertain, with increases, negligible change and decreases reported (e.g. Specht and West, 2003; Lima et al., 2006; Harper et al., 2012). Some variation may be explained by time since reforestation, as generally there are initial decreases in SOC stocks in the first five years after reforestation, followed by recovery to pre-establishment levels (approx. 10–30 years), and then a gradual increase (e.g. Paul et al., 2002). However, most of the variability in SOC stocks following reforestation reflects differences in sequestration rates among climates, soil types, tree species and previous land uses (Guo and Gifford, 2002; Paul et al., 2002; Laganière et al., 2010).

Previous land use can be an important determinant of sequestration of SOC following reforestation, with increases in stocks on ex-cropland and predominantly losses on ex-pasture (Guo and Gifford, 2002; Laganière et al., 2010). Climate can have a strong influence, with increases in tropical and sub-tropical regions compared with small decreases in temperate and Mediterranean-type regions (e.g. Paul et al., 2002). Soils with high clay content generally have a larger capacity to accumulate SOC than those with lower clay content (Laganière et al., 2010; Paul et al., 2002). Further, the tree species planted can affect carbon sequestration, with increases in SOC stocks under some nitrogen-fixing acacia trees (Kasel et al., 2011; Forrester et al., 2013), although these effects may be species-specific (Hoogmoed et al., 2014), whereas decreases in SOC stocks have been found under pines (Parfitt et al., 1997; Turner and Lambert, 2000).

Accumulation of plant litter is an additional store of carbon in forests until a steady state between litterfall and decomposition is reached (Paul et al., 2003). Rates of litter accumulation in native and plantation forests differ widely among forest types and species (e.g. Spain, 1984; Adams and Attiwill, 1991; Fernandez-Nunez et al., 2010), predominantly reflecting differences in litter quality and climate (Prescott, 2010). Pine plantations can accumulate particularly thick and recalcitrant litter layers (e.g. Paul et al., 2003; Paul and Polglase, 2004) compared with those under other plantation species (e.g. Turner, 1986; Harper et al., 2012). Comparable studies under mixed-species plantings are limited, but suggest that thick layers of up to approximately15 t dry matter (DM) ha^{-1} can accumulate within two decades when eucalypts are planted (Cunningham et al., 2012).

SOC exists as a diverse mix of organic materials with different susceptibilities to biological decomposition (Baldock et al., 2013a). Reforestation may change the molecular form of SOC and, consequently, increase the stability of the stock (Cunningham et al., 2015b). For a given organic carbon content, the provision of energy to soil organisms should increase with increasing proportion of plant litter-like components and decrease with increasing proportion of biologically-recalcitrant charcoal or char-like components (Baldock et al., 2013a). Reforestation may increase inputs of more resistant SOC to soil but generally there is little increase in resistant humic material within three decades, although earlier increases have been observed (e.g. Del Galdo et al., 2003; Cunningham et al., 2015b). Understanding the form of SOC sequestered after reforestation (i.e. its stability) is important in predicting the longer-term rates of sequestration and resilience of carbon stocks to future change (e.g. with climate change), and to calibration and verification of process-based models of turnover and accumulation of SOC.

Establishment of mixed-species environmental plantings (i.e. plantings of native tree and shrub species established for environmental benefits with no intention to harvest) on agricultural land can be an economically-viable option in lower rainfall (<1000 mm y^{-1}) regions (Crossman et al., 2011; Polglase et al., 2013). Indeed, environmental plantings are increasingly being established to sequester carbon because of their co-benefits to the environment and biodiversity (e.g. Mitchell et al., 2012). Consequently, measurement and modelling of biomass carbon in environmental plantings across a broad range of climatic and management conditions has been the focus of recent work (e.g. Paul et al., 2015). In contrast, there are limited measurements of changes in soil and litter carbon under such plantings (e.g. Cunningham et al., 2015b), and little is known about their potential to sequester carbon in litter and soil compared with production forests (Cunningham et al., 2015a). Global meta-analyses of soil carbon sequestration following reforestation (Silver et al., 2000; Guo and Gifford, 2002; Paul et al., 2002; Laganière et al., 2010) include few studies of mixed-species plantings, and even meta-analyses of biomass accumulation in mixed-species plantings have been dominated by plantings with only two species (Piotto, 2008; Hulvey et al., 2013). Further, environmental plantings are highly variable, being established across a much broader range of climates, previous land uses and landscape positions than a given commercial plantation type (Paul et al., 2015).

Here, we assessed potential predictors of soil carbon sequestration under environmental plantings, which will inform their future establishment, calibration of carbon accounting models and development of policy on carbon markets. A national dataset of 117 Australian sites was collated and analysed, which represented much of the temperate and Mediterranean-type climates across the continent. Three key research questions were addressed in relation to changes in carbon sequestration following reforestation with environmental plantings:

1) Are there significant differences in stocks of total SOC and its fractions (particulate, humus, resistant)?
2) Are estimates of carbon sequestration significantly increased when stocks of litter are included?
3) What are the key site conditions and management practices that determine the magnitude of differences in SOC and litter stocks?

2. Methods

2.1. Study sites

New and existing data were collated from 117 mixed-species environmental plantings (subsequently termed 'environmental plantings') established on agricultural land. Plantings were across southern and eastern Australia (latitude −30.9 to −38.7 S, longitude 117.4–150.3 E), and covered the range of rainfall zones where planting occurs (380–1147 mm y^{-1}; Table 1, Fig. 1). Thirty-six new sites were measured to improve the representativeness of plantings with respect to age, previous land use, productivity (aboveground biomass increment) and soil texture (Table 1). Environmental plantings are often established along stream banks to reduce erosion or in areas with shallow water tables to mitigate dryland salinity by minimising recharge (George et al., 1999). Thus sites were selected to include both dryland plantings across a range of landscape positions (N = 97) and riparian plantings (N = 20).

Previous land use at the sites included grazing, cropping, and rotational cropping and grazing (Table 1). For analysis, we

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