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The sequestration and turnover of soil organic carbon in subtropical leucaena-grass pastures

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ABSTRACT

The sequestration of soil organic carbon (SOC) in agricultural systems has the potential to partially mitigate climate change by removing carbon dioxide (CO_2) from the atmosphere. Furthermore, incorporating forage legumes into a grazing system may aid in C storage, as mature unfertilized pasture soils are typically nitrogen (N) limited. *Leucaena leucocephala*, a leguminous shrub, is often incorporated into grazing systems to provide a source of protein for cattle production. Additionally, leucaena improves the N fertility of grazing lands. Despite this, there is limited research on the C and N dynamics beneath leucaena-grass pastures, particularly at depth in the soil profile (1 m). We assessed the potential of leucaena to sequester SOC by estimating the origin (C_3 or C_4), quantity and vertical distribution of SOC stocks. A chronosequence of seasonally grazed leucaena stands (0, 9, 22, 34, 40 years) were sampled for organic C and natural $\delta^{13}C$ abundance. Pasture type affected SOC stocks within the upper 0.2 m (grass < leucaena mid-row = leucaena row). SOC stocks were also affected by leucaena stand age. In the 0–0.3 m zone, SOC increased by 17–30% over 40 years, equating to a sequestration rate of 280 kg ha^{-1} year^{-1}. Soil $\delta^{13}C$ values were depleted below the C_3 leucaena rows (−16‰) compared to the C_4 grass pasture (−13‰). However, the majority of SOC displayed a C_4–C signature. Hence, SOC sequestration primarily occurred due to N accretion by leucaena (36 kg N ha^{-1} year^{-1}) contributing to the increased C_4 grass productivity, humus formation and slowed SOC decomposition. Therefore, there is a need to maintain soil fertility in grazed pastures to ensure SOC stocks are accreted and conserved.

1. Introduction

The global focus on climate change has led to an increasing interest in soil C and in particular, on the potential for agricultural systems to sequester atmospheric CO_2 as a means of mitigating greenhouse gas emissions. The SOC pool is one of the largest near-surface C stores on Earth (Schlesinger, 1995). It contains an estimated 1500 Gt of C, or 80% of the total terrestrial C store (Amundson, 2001; Richards, 2007). Likewise, Australian agricultural soils contain 70% of the nation's terrestrial SOC sink, which equates to approximately 25 Gt of C in the top 0.3 m depth (Viscarra-Rossel et al., 2014). Managing these agricultural soils to maximize SOC storage, within the limitations of climate, soil type and land use requires knowledge of the source, size and turnover time of different SOC pools.

Within the Australian agricultural sector, grassland management for beef cattle production is a major form of land use (Burle etal., 2003). Over 430 million ha or 56% of the Australian continent is currently under extensive livestock grazing (Catchpoole and Blair, 1990), with more intensive production systems, based on improved pastures, accounting for 6% of the total land area (Burle et al., 2003). *Leucaena leucocephala* (Lam.) de Wit ssp. *glabrata* (Rose Zarate) is a perennial leguminous shrub, commonly incorporated in beef production systems due to its highly palatable, nutritious foliage which yields significant benefits in terms of live weight gain. Over 150 000 ha of leucaena have been planted throughout central and south-eastern Queensland since 1980 and based on current estimates, this area is likely to reach 300 000 to 500 000 ha by 2017 (Shelton and Dalzell, 2007). In grazing systems, leucaena is typically planted in single or twin hedgerows separated by a 5 to 8 m inter-row strip of improved grass pasture (Radrizzani et al., 2010a, 2010b).

Leucaena-grass pastures are thought to offer a number of environmental benefits including the sequestration of atmospheric CO_2 in the woody biomass of individual plants. Additionally, leucaena stands have the potential to increase SOC storage over the long-term (Radrizzani et al., 2011). Typically, mature grass pasture soils are N limited, constraining their ability to sequester SOC (Graham et al., 1981). Significant amounts of N and phosphorus (P) are required to support plant growth, maximize net primary productivity and sustain a functioning

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Table 1
Attributes of the leucaena (and grass) sites sampled on Brian Pastures Research Station.

Year of leucaena establishment	Age (years)	Regional soil classification	Soil Order
1969	40	Graham	Vertisol (Udic Pellusterts)
1975	34	Graham	Vertisol (Udic Pellusterts)
1975	34	Browns	Alfisol (Udic Paleustalfs)
1987	22	Graham	Vertisol (Udic Pellusterts)
2000	9	Graham	Vertisol (Udic Pellusterts)

microbial community (Radrizzani et al., 2011).

Current literature suggests pastures containing legumes have a greater capacity to increase SOC (Kang et al., 1985; Barrios et al., 1996; Robles and Burke, 1997). In line with this, leucaena is reported to improve soil chemical fertility (N and P) in tree plantations (Midwood and Boutton, 1998; Clayton, 2007), alley cropping systems (Kang et al., 1985; Onim et al., 1990) and grazed pastures (Onim et al., 1990; Fernandes and Krull, 2008). Other studies have confirmed the C sequestration benefits of incorporating leucaena foliage as a green manure or soil amendment within intensively managed agro-forestry systems (Isaac et al., 2003a, b; Diels et al., 2004; Youkhana and Idol, 2011). Despite this, limited literature exists on the SOC status of grazed, *in-situ* leucaena-grass pastures. Radrizzani et al. (2011) reported that leucaena pastures accumulated an extra 3.0 to 5.3 t ha^{-1} of SOC in the upper 0.15 m of a Vertisol profile, compared with adjacent buffel grass (*Pennisetum ciliare* L.) pasture over 20 to 38 years. This equates to a 0.12 to 0.22% increase in the SOC concentration. By extrapolating the data, Shelton and Dalzell (2007) estimated an additional 1.98 Mt of $CO_{2\text{-e}}$ (0.54 Mt of C) were sequestered by the 150 000 ha of leucaena plantings across Queensland in the topsoil (0.15 m) alone. As the majority of leucaena has been planted on fertility-depleted cultivation land, especially low in P and S (Radrizzani et al., 2011), the above estimate was considered conservative. Other studies suggest the SOC concentration could increase by > 5% within 10 years of establishing legume-grass pastures (Cullen and Hill, 2006; Silburn et al., 2007). In contrast, Carter et al. (1998) found a decrease in SOC in the surface horizon but a net accretion below 0.2 m in a leucaena-grass pasture planted on a Vertisol. Compared with buffel pasture, leucaena stored an extra 5 t ha^{-1} to a depth of 0.8 m over 10 years. Hence, further research is required to clarify the observed trends and elucidate the mechanisms and processes of SOC storage in the profile.

The difference in SOC dynamics following a change in pasture species (i.e. C_4 to C_3 dominant vegetation), is frequently studied by quantifying the natural abundance of stable C isotopes ($\delta^{13}C$) in the soil profile. Using these techniques, it is possible to determine the quantity, origin, residence time and turnover rate of SOC (Balesdent and Mariotti, 1996; Boutton, 1996; Ellert and Rock, 2008). Vegetation with C_3 (most trees) and C_4 (tropical grasses) photosynthetic pathways yield different $\delta^{13}C$ isotopic signatures and these differences are largely maintained as plant residues undergo decomposition in the soil (Farquhar et al., 1982; Ehleringer et al., 2000). This means SOC derived from leucaena (a C_3 plant) can be distinguished from that produced by tropical grasses (predominantly C_4 plants). Applying a simple mass balance equation, based on a mixing model, allows the estimation of leucaena (C_3) and grass (C_4) contribution to SOC.

We investigated the sequestration and turnover of SOC in subtropical, leucaena-grass pastures of southern Queensland, Australia. A chronosequence of leucaena plots, aged from 9 to 40 years were used to study soil C dynamics following a change in vegetation type and subsequently, grazing land management. The objectives of this study were to: (i) estimate the origin, quantity, vertical distribution and mean residence time (MRT) of SOC in the profile; (ii) assess the difference in SOC and total soil N stocks between pasture types (leucaena and pure-grass pastures), soil types (Alfisol and Vertisols) and over time with increasing age of leucaena stands.

2. Materials and methods

2.1. Site description

The study site was located on Brian Pastures Research Station (25°39′S, 151°45′E, elevation 131 m), approximately 17 km east-south east of Gayndah, in southern Queensland, Australia. It encompasses two blocks on the western side of Barambah Creek, covering a total area of 3830 ha (Reid and Sorby, 1986). A land capability assessment classified the study area as best suited to dryland agriculture and grazing (Reid and Sorby, 1986). The research station falls within a sub-humid, subtropical climatic zone, receiving a mean annual rainfall of 762 mm (Queensland Department of Primary Industries, 2002). Precipitation is highly variable and concentrated in the summer months, with 70% of rainfall received between October and March (Reid and Sorby, 1986). The mean maximum temperature (January) for the region is 27.7 °C with a corresponding minimum (July) of 14.2 °C (Queensland Department of Primary Industries, 2002). Pan evaporation exceeds the mean annual rainfall, averaging 1935 mm per year (Queensland Department of Primary Industries, 2002).

The region around Gayndah and Ban Ban Springs has a long and well documented grazing history. Pastoral interests were first noted in 1846, with extensive ringbarking occurring between 1891 and 1901. The native vegetation prior to clearing consisted of open Eucalypt forest and woodlands (Nelder and Paton, 1986). The tropical forage tree legume, *Leucaena leucocephala* was first established in 1969 in six adjacent plots of predominantly buffel grass. Further plantings were undertaken in 1975, 1976, 1986, 1987, 1989 and 2000 on a range of soil types and topographical features (Table 1, Russ Tyler, personal communication). The majority of sites were planted with the commercial cultivar (*Leucaena leucocephala* ssp. *glabrata* cv. Peru). However, the 2000 planting made use of the Tarramba cultivar (*Leucaena leucocephala* ssp. *glabrata* cv. Tarramba) (Russ Tyler, personal communication). The plots used in this study had never received N fertilizer and were grazed on a seasonal basis (Russ Tyler, personal communication). The dominant grass species in the leucaena and grass pastures were green panic (*Panicum maximum var. trichoglume*), blue grass species (*Bothriochloa* and *Dichanthium* spp.), buffel grass and black spear grass (*Heteropogon contortus*) (Nelder and Paton, 1986).

A detailed description of the leucaena establishment and fertilizer history at Brian Pastures Research Station is given by Radrizzani (2009) and Radrizzani et al. (2010b). Briefly, the 9 year old site was established after the cropping phase of a 3 year ley-pasture rotation, while the 40 year old leucaena was planted into a fallowed seed bed that had previously been under native grass pasture. The history of the 22 and 34 year old sites is uncertain. Leucaena seed was inoculated with rhizobia prior to being planted at 2 kg ha^{-1} in the 9 year old site and 4 kg ha^{-1} in the older stands (22, 34 and 40 years). Phosphorus (22 kg ha^{-1}) and sulfur (S; 28 kg ha^{-1}) fertilizer was applied as per best management practices for leucaena pastures. Following leucaena establishment the inter-rows were recolonized by endemic grasses. A seasonal grazing regime was imposed at Brian Pastures Research Station (Radrizzani, 2009). Briefly, the grass pastures were grazed year round at a stocking rate of 0.625 animal equivalents (AE)/ha (1 AE is a 400 kg steer). Cattle grazed the leucaena pastures between May and