Soil carbon: variation across the landscape

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Abstract: *Soil carbon sequestration is influenced by soil type, climate, vegetation and management. This paper discusses results from 48 field observations of total carbon concentration and carbon stock in soil from the Monaro and Boorowa regions, south-eastern NSW. Three comparisons were made: soil type (basalt- vs granite-derived soil), perennial pasture type (native vs introduced) and climate (summer dominant vs equiseasonal rainfall). Basalt derived soil had a significantly higher ($P < 0.05$) total carbon concentration (g/100g) throughout the soil profile (to 0.70 m) compared with granite derived soil; the mean mass of C (to 0.70 m) was 159 Mg C ha^{-1} in basalt derived soil 76 Mg C ha^{-1} in deep granite derived soil and 43 Mg C ha^{-1} in shallow granite derived soil. However, there was considerable variation within each soil type group. There was no significant difference in the mass of C in soil between native and introduced pastures in either region. There was a significant difference ($P < 0.05$) in C stock due to climate; with deep granite derived soil in the Monaro region containing more C than similar soil in the Boorowa region (76.50 vs 51.80 Mg C ha^{-1} to 0.70 m). Observations made in this study suggest that sequestration of C in soil under perennial pastures is largely driven by soil type and climate. The variation in C stock within a given soil type and climate suggest that there is some potential for management to increase the amount of organic matter in soil in the Monaro and Boorowa regions.*

Key words: carbon concentration, carbon stock, perennial pasture, climate, carbon saturation, carbon protection

Introduction

Sequestration of carbon (C) in agricultural soils has been promoted as an important tool to mitigate climate change. Before entering into a scheme where soil C is traded, it is important to understand how soil C varies across the landscape and what is driving the potential for soil to sequester carbon.

In soil, organic matter (OM) is a diverse group of organic materials comprised of partially decomposed organic residues, microbes, humic substances, and charcoal; all differ in chemical composition and stage of decomposition. Carbon is the main element present in soil OM, on average making up 58% by weight (Page *et al.* 1982).

The amount of C measured in soil is influenced by soil type, climate, vegetation and land management (Blanco-Canqui and Lal 2008, Lal 2004, Sherrod *et al.* 2005, Sparling 1992). To increase the amount of C in soil, the C inputs need to be greater than the losses. Inputs are derived from biomass production (and retention) and the application of organic amendments that are high in C, such as mature compost and pyrolysed OM. Organic C is removed from the soil through decomposition of OM by micro-organisms and soil erosion. When there is a net gain in the mass of C in soil, the soil is said to be sequestering carbon.

Biomass production, or 'herbage mass', is largely determined by the moisture content, nutrient level and temperature of soil. These factors are driven by inherent soil physiochemical properties and climate factors such as rainfall, temperature and evaporation. Soil physical and chemical attributes and climate also influence the activity of soil microbes and hence the rate of OM decomposition (Six *et al.* 2002, Sparling, 1992). Knowledge of these environmental characteristics assists in understanding why C varies across the landscape and in identifying areas with greater potential to sequester C in soil (Sherrod *et al.* 2005).

More than 80% of NSW agricultural land is under pasture (Chan *et al.* 2010). It has been suggested that well-managed, perennial pastures may help to achieve the soil's maximum C sequestration potential (Chan *et al.* 2009, Chan *et al.* 2010, Lal 2004, Post and Kowon 2000, Sanderman *et al.* 2010). Pastures contribute significant amounts of above- and below-ground organic residues to the soil. Perennial pastures in particular, produce more below ground inputs with greater soil persistence, that is; residues with higher C:N ratios and lignin content rendering them less vulnerable to decomposition, than most agricultural crops (Sparling 1992). It has also been suggested that perennial pastures may increase the amount of OM in soil beyond the levels under Australian native forests by enhancing soil aggregation thereby protecting OM from decomposition (Oades 1995).

This paper examines the variation in total C concentration and C stock (T/C/ha) in soil under perennial pastures with a) soil type, b) pasture type (native *vs* introduced) and c) climate in south-eastern NSW.

Methods

Study sites and sampling

The Monaro and Boorowa regions are located in the Southern Tablelands of NSW (Figure 1). Both regions have similar average annual rainfall (Monaro; 500mm and Boorowa 610mm). However, the Monaro region receives most of the annual rainfall in summer compared with the Boorowa region which has an equiseasonal rainfall pattern. In the Monaro region, both granite derived duplex soils (Kurosols and Chromosols; Isbell 2002) and basalt derived gradational soils (Dermosols and Ferrosols; Isbell 2002) were sampled in winter 2009. In the Boorowa region, granite derived duplex soils were sampled in autumn 2010. In both regions, the granite derived soils are characterised by coarse textured sand over light to medium clay, naturally acidic with low water holding capacity and low fertility. In contrast, the basalt derived soils sampled on the Monaro are characterised by clay loam texture over light and medium clay with high water holding capacity and high fertility. Granite derived soils on the Monaro where divided into two categories; deep granite derived soils, where the C horizon was deeper than 0.50 m and shallow granite derived soils where the C horizon was within 0.50 m of the soil surface.

All sites had perennial pasture base established before 1998. Where possible, paddocks with the same soil type (including depth to B horizon) and landscape position were paired to include a native pasture within 100 m of an introduced perennial pasture. Table 1 provides site details and attributes. Across both regions, the native perennial pastures were typically composed of wallaby grass (*Austrodanthonia* spp), Microlaena (*Microlaena stipoides*), spear grass (*Austrostipa scabra*) and also in the Monaro region; poa tussock (*Poa labillardierei*). Introduced perennial pastures were typically phalaris (*Phalaris aquatica* L.) and cocksfoot (*Dactylis glomerata* L.). Both pasture types included exotic annual species such as subterranean clover (*Trifolium subterraneum*) and small amounts of broad leaf weeds.

One sampling quadrat, 40m x 40m was located in a representative area of the paddock and soil cores were taken to a depth of 0.70 m and divided at depth intervals of 0–0.05, 0.05–0.10, 0.10–0.20, 0.20–0.30, 0.30–0.40, 0.40–0.50 and 0.50–0.70 m for bulk density (BD) and chemical analyses. Four cores at each site were taken for BD observations (McKenzie *et al.* 2000). Bulk density was determined on samples dried at 105°C as described by Dane and Topp (2002). Results were calculated as BD in Mg/m^3 (equivalent to g/cm^3) on an oven-dry basis to the nearest 0.01 Mg/m^3. Chemical analyses were conducted on soil from a composite sample of sixteen cores from each site collected using a hydraulically driven core sampler. Soil from

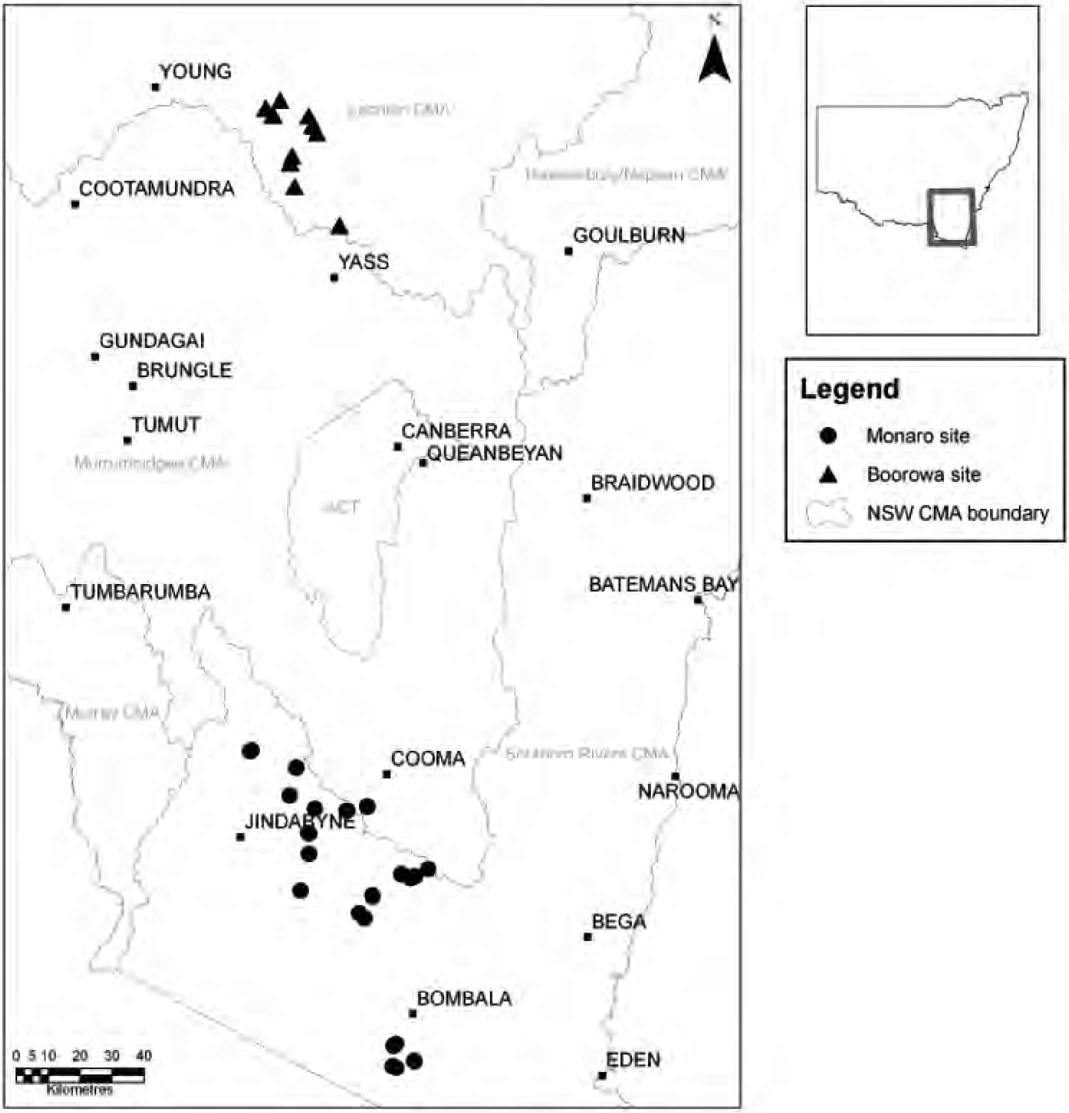

Figure 1. Location of the Monaro and Boorowa study sites in south-eastern NSW. The solid circles indicate the Monaro sites and the solid triangles indicate the Boorowa sites.

Table 1. Number of study sites and site descriptions for Monaro and Boorowa regions.

Region	Geology	Pasture type	ID	Number of sites
Monaro	Basalt	Introduced	MonIB	6
		Native	MonNB	6
	Granite – Deep	Introduced	MonIDG	6
		Native	MonNDG	6
	Granite – Shallow	Native	MonNSG	6
Boorowa	Granite – Deep	Introduced	BooIDG	9
		Native	BooNDG	9

each depth interval was bulked to produce representative samples for the soil depth layers.

Analytical methods

Soil samples were oven-dried at 40°C, passed through a 2mm sieve and ground to <0.5mm using a single puck mill head (Rayment and Higginson 1992; Method 1B1). Soil samples were tested for carbonates (inorganic C) using HCl and observing the degree of effervescence (Rayment and Lyons 2011; Method 19D1). As there was no effervescence recorded, no pre-treatment for inorganic C was provided before analysis. Total Carbon (TC) was determined on 2g of finely ground soil using a LECO combustion furnace (CNS 2000) as previously described (Merry and Spouncer 1988, Rayment and Higginson 1992; Method 6B3). Results are reported as TC (g/100g).

Results for this paper are also reported as carbon stock in Mg C ha^{-1} calculated by;

Carbon stock (Mg C ha^{-1}) = Carbon concentration (g/100g) × bulk density (g/cm^3) × depth (cm)

Statistical analysis

Statistical analyses were performed using GENSTAT v.8 (VSN International Ltd, UK) software. Differences at $P = 0.05$ between means of C stock (Mg C ha^{-1}) for comparison of sites were assessed using one- and two-way ANOVA.

Results and discussion

Soil type

At all sites, C concentration in soil decreased with an increase in depth (Figure 2). Basalt derived soil had a significantly higher ($P < 0.05$) C concentration throughout the soil profile compared with granite derived soil. In the surface soil (0.20 m) in the Monaro region, the deep granite derived soil had a significantly higher ($P < 0.05$) C concentration than similar soils in the Boorowa region. There was no significant difference in the C concentration in granite derived soil from the Monaro or Boorowa regions deeper than 0.30 m.

In the Monaro and Boorowa regions, the main source of OM in soil came from herbage mass production, as organic amendments are not commonly applied. These OM contributions were greatest in the top soil and have resulted in higher concentrations of C in the surface 0–0.10 m soil. This section of the soil profile also has the highest amount of biological activity (Sparling 1992). Bird *et al.* (2003) also reported that, regardless of soil type, the majority of OM in soil is found close to the soil surface.

Soil type significantly influenced the mass of C in soil in the Monaro region. The mean mass of C (to 0.70 m) was 159 Mg C ha^{-1} in basalt derived soil, 76 Mg C ha^{-1} in deep granite derived soil and 43 Mg C ha^{-1} in shallow granite derived soil. There was considerable variation in the mass of C within each soil type group. Basalt derived soils ranged from 115 to 192 Mg C ha^{-1} (24.5 sd), deep granite derived soils ranged from 45 to 130 Mg C ha^{-1} (26.4 sd) and shallow granite derived soils ranged from 35 to 57 Mg C ha^{-1} (9.3 sd) to 0.70 m (Figure 3). There was a significant difference between the mean mass of C (0–0.70 m) on basalt and deep granite derived soils ($P < 0.001$), basalt and shallow granite derived soils ($P < 0.001$) and deep granite and shallow granite derived soils ($P < 0.05$).

Soil structure and clay content are reported to positively influence the accumulation of OM in soil (Conant *et al.* 2003, Oades 1995, Motavalli *et al.* 1994, Rees *et al.* 2005, Grandy and Robertson 2007). Basalt derived soil in the Monaro region typically had > 20 % clay in the A horizon and > 35 % clay in the B horizon and was moderately to well-structured throughout

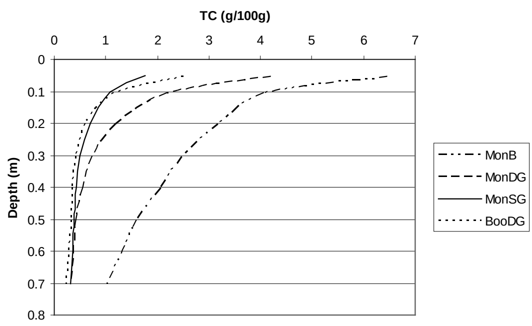

Figure 2. Mean soil C concentration profiles for study sites on the Monaro (basalt; MonB, deep granite; MonDG and shallow granite; MonSG) and in the Boorowa region (deep granite; BooDG).

the profile. These high clay content soils had inherently higher nutrient contents, particularly phosphorus, compared with granite derived soil and had a greater water holding capacity. These attributes are important for herbage mass production and correspondingly high below ground root production. Furthermore, clay particles are more effective than sand and silt particles in protecting OM from decomposition in soil. Clay particles can physically protect OM by limiting micro-organism access and chemically protect OM by sorbing organic molecules and complexing with clay minerals to form organo-mineral associations (Bird *et al.* 2003, Conant *et al.* 2003, Shepherd *et al.* 2001, Six *et al.* 2002, West and Six 2007). This 'protection' of OM from decomposition has implications for C sequestration.

Pasture type

There was no significant difference in the mass of C in soil between native and introduced perennial pastures in the Monaro and Boorowa regions. The mass of C in soil under introduced and native pastures was not significantly different in the Monaro basalt derived soils, Monaro deep granite derived soils or the Boorowa deep granite derived soils (Figure 4).

It was hypothesised that there would be a difference in the mass of C under native and introduced perennial pastures. In both regions, introduced perennial pastures were established more than 10 years ago (more than 30 years on the Monaro) to increase herbage mass production and quality. It was anticipated that the increase in biomass production would increase the amount of OM in soil through greater below-ground root production. West and Six (2007) estimated that C sequestration in soil following the establishment of a well managed introduced perennial pasture would peak at 5 years and continue at a declining rate for up to 45 years.

Observations of no significant difference between native and introduced perennial pastures agree with Chan *et al.* (2010) . These authors believed that the differences in C sequestration were not large enough to detect between the pasture types. This explanation was considered for our observations; that is, the total mass of C in soil is so large that the contribution of OM from herbage mass production from either pasture type is negligible. However, there were no significant differences for soil type or for location despite a significant range in the mass of C. There was no significant difference in pasture type in the high C content basalt soils on the Monaro (115 to 192 Mg C ha^{-1}) or the lower C content deep granite derived soils in the Boorowa region (41 to 71 Mg C ha^{-1}). We therefore considered two additional explanations. Firstly, that both soil types have reached a point of C saturation, so any additional biomass inputs from the introduced pasture would not lead to greater C stock. It has been argued that soils with a high amount of OM accumulate less C, and at a slower rate, than those with low amounts of OM

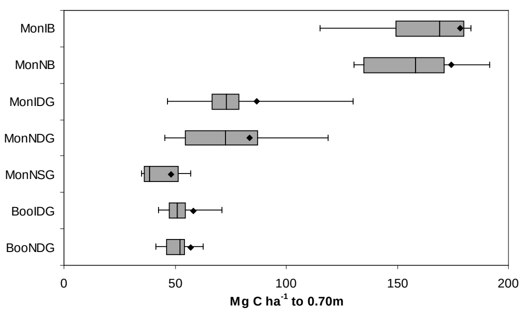

Figure 3. Box plot of the mass of C (Mg C ha^{-1}) in soil for study sites on the Monaro (basalt; MonIB and MonNB, deep granite MonIDG and MonNDG and shallow granite; MonNSG) and in the Boorowa region (deep granite; BooIDG and BooNDG). The sample minimum, lower quartile, median, mean, upper quartile and the sample maximum are graphed.

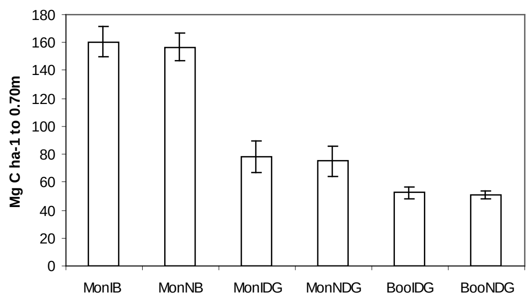

Figure 4. Mean mass of C (Mg C ha^{-1} to 0.70 m) in soil under perennial pastures in the Monaro (basalt; MonIB and MonNB and deep granite; MonIDG and MonNDG) and Boorowa regions (deep granite; BooIDG and BooNDG). Error bars are the standard error of means.

(West and Six 2007). However, this is unlikely to be the reason as the range in the mass of C within the environments we examined indicates that there are sites that have not yet reached C saturation. An alternative explanation is that in response to the preceding 10 years of dry conditions at both locations, the introduced pastures have been under performing due to moisture limitations and inadequate nutrient management. Regardless, the variation in the mass of C potentially represents an opportunity for additional C sequestration through the adoption of appropriate management practices such as maintaining adequate pasture nutrition, ameliorating soil constraints to plant growth and strategically grazing to maintain groundcover.

Climate

There was a significant difference (P <0.05) between the mean mass of C in deep granite derived soils in the Monaro and Boorowa regions (Figure 5). In the Monaro region, the mean mass of C in soil under perennial pastures was 76.50 Mg C ha^{-1} (26.4 sd) to 0.70 m while in the Boorowa region, the mean mass of C in soil was 51.80 Mg C ha^{-1} (7.5 sd) to 0.70 m.

Climate seems to have had a significant influence on C sequestration on the Monaro (cf. Boorowa). Climate influences C sequestration by influencing the rate of decomposition and potential herbage mass growth. Micro-organisms are more active in warm humid environments in response to soil moisture and soil temperature and therefore decompose OM more rapidly than in dry/cold and dry/hot environments (Cleveland *et al.* 2006).

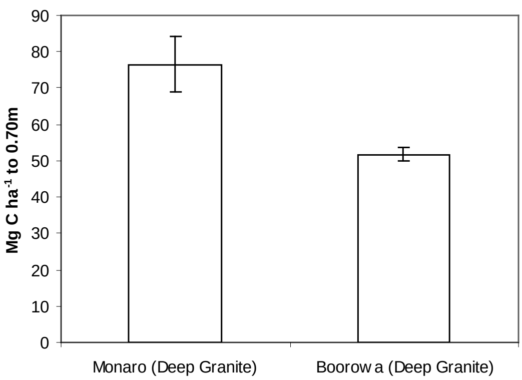

Figure 5. Mean mass of C (Mg C ha^{-1} to 0.70 m) in deep granite derived soil under perennial pastures on the Monaro and in the Boorowa region. Error bars are the standard error of means.

Both study regions have similar soil types; hence a similar capacity to protect OM, and similar annual herbage mass production, pasture composition, grazing and nutrient management. However, the Monaro region is 800 to 1000 m above sea level and receives most of the annual rainfall in summer compared with the Boorowa region which is 550 m above sea level and has an equiseasonal rainfall pattern (Bureau of Meteorology 2012). Furthermore, the Monaro region is on average 4°C colder in winter and receives average minimum temperatures that are less than 5°C for more than one month longer than the Boorowa region (Bureau of Meteorology 2012). The Monaro region also experiences irregular rainfall due to a rain shadow effect associated with the Snowy Mountain range. It is anticipated that colder soil temperatures and more variable rainfall have limited OM decomposition and therefore there has been a net increase in C sequestration in the Monaro region relative to that in the Boorowa region.

Conclusions

Observations made in this study suggest that sequestration of C in soil under perennial pastures is largely driven by soil type and climate. The variation in C stock within a given soil type and climate indicate areas of the landscape where there is some potential for appropriate management to increase the amount of OM in soil in the Monaro and Boorowa regions.

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