CSIRO PUBLISHING
Soil Research, 2013, **51**, 668–679
http://dx.doi.org/10.1071/SR12376

Land-use and historical management effects on soil organic carbon in grazing systems on the Northern Tablelands of New South Wales

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Abstract. We examined soil organic carbon (SOC) concentration (mg g^{-1}) and total organic carbon (TOC) stock (Mg ha^{-1} to 30 cm soil depth) in three pasture systems in northern New South Wales: improved pasture, native pasture, and lightly wooded pasture, at two sampling times (2009 and 2011). No significant difference was found in SOC or TOC between sample times, suggesting that under the conditions we examined, neither 2 years nor an intervening significant rainfall event was sufficient to change the quantity or our capacity to detect SOC, and neither represented a barrier to soil carbon accounting. Low fertility, lightly wooded pastures had a slightly but significantly lower SOC concentration, particularly in the surface soil layers. However, no significant differences in TOC were detected between the three pasture systems studied, and from a carbon estimation perspective, they represent one, single dataset. A wide range in TOC values existed within the dataset that could not be explained by environmental factors. The TOC was weakly but significantly correlated with soil nitrogen and phosphorus, but a more significant pattern seemed to be the association of high TOC with proportionally larger subsoil (0.1–0.3 m) organic carbon storage. This we attribute to historical, long-term rather than contemporary management. Of the SOC fractions, particulate organic carbon (POC) dominated in the surface layers but diminished with depth, whereas the proportion of humic carbon (HUM) and resistant organic carbon (ROC) increased with soil depth. The POC did not differ between the pasture systems but native pasture had larger quantities of HUM and ROC, particularly in the surface soil layers, suggesting that this pasture system tends to accumulate organic carbon in more resistant forms, presumably because of litter input quality and historical management.

Received 23 December 2012, accepted 2 August 2013, published online 20 December 2013

Introduction

Across Australia and internationally, attention has been focussed on the capacity of soils to store additional carbon. Globally, soils are estimated to contain around 1500 gigatonnes (Gt) of organic carbon in the top 30 cm, which is significantly more than is contained in vegetation and the atmosphere combined (Batjes 1996; Grace 2004; Houghton 2005). However, soil organic carbon (SOC) has historically been depleted as a result of land conversion, soil disturbance, and agricultural intensification. Globally, it has been estimated that soils have lost 42–78 Gt of their original carbon because of these management pressures (Lal and Follett 2009).

Carbon-depleted soils offer a significant opportunity for additional carbon storage, and the world's soils are believed to have the capacity to store an additional 0.4–1.2 Gt C $year^{-1}$ with the introduction of more judicious land-management practices (Lal 2004), and they therefore have a potentially significant role in offsetting greenhouse gas emissions elsewhere (Swift 2001). In Australia and internationally, management practices are therefore being sought that can store additional soil carbon while maintaining agricultural production and food security.

By international standards, soils in Australia are low in organic carbon. However, several land-use and management practices have been proposed that have potential for increased carbon storage (Sanderman *et al*. 2010). Among these, pasture establishment and management in temperate regions of Australia have been promoted as a means of increasing SOC stock (e.g. Chan *et al*. 2010*a*, 2010*b*). Research undertaken in these regions has demonstrated that SOC stocks are typically larger under perennial pasture compared with soils subject to ongoing cultivation (Wilson *et al*. 2008, 2010, 2011; Young *et al*. 2005, 2009), presumably as a consequence of greater biomass carbon inputs under pasture systems (Baldock *et al*. 2009).

Uncertainty remains regarding the effects of pasture type and management on organic carbon stocks. For example, Chan *et al*. (2010*c*) and Sanderman *et al*. (2010) suggested that pastures that are regularly fertilised, limed, or irrigated could increase SOC by 0.1–0.3 Mg C ha^{-1} $year^{-1}$. Such results were typically derived from controlled agricultural trials or field experiments. However, Wilson *et al*. (2011) found that few differences in total SOC could be detected across grazing systems in northern New South Wales (NSW). Orgill *et al*. (2012) examined a range of pasture types and management approaches across southern NSW landscapes and similarly found no significant difference between the various systems studied. Orgill *et al*. (2012) concluded that grazing management explained only a limited amount of SOC variability but soil fertility and parent material were significant determinants of the quantity of soil carbon.

Although the effects of pasture management on SOC concentration and stock might be limited, it is possible that the SOC cycling could be affected by management system. The rate and nature of this cycling can be detected to some degree by examining the various fractions of SOC in the soil. For example, a high proportion of more labile particulate organic carbon (POC), as distinct from more stable humic (HUM) or resistant (ROC) fractions, might be indicative of more rapid cycling and a less stable SOC stock (Conant *et al*. 2001; Baldock 2007), and SOC fractions might be a more sensitive indicator of SOC change than bulk SOC stock (Shen *et al*. 2008).

Only a limited amount of work has systematically quantified the carbon stocks of Australian soils and compared various land-use and management systems to evaluate their carbon storage potential. The Soil Carbon Research Program (SCaRP) was therefore initiated across Australia in 2009 with the aim of assessing current carbon stocks across a range of representative agricultural land-use systems, focussing on those land uses that were believed to hold the most promise for carbon storage. Although this approach has limitations for the prediction of SOC change from one land use to another, it provides an indication of relative quantities of SOC that are likely to exist under different land uses at a defined point in time.

The work reported here was a part of the NSW component of the SCaRP program and focussed on three pasture types on the Northern Tablelands of NSW: native pasture, improved pasture, and lightly wooded pasture. The work was undertaken in two discrete stages with duplicate sites being sampled at each stage. In 7 of the 10 years that preceded the first sampling period in 2009, total annual rainfall (578–724 mm) was well below the long-term average (785 mm, BoM 2012). However, the years 2010 and 2011, after which the second sampling was undertaken, both had annual rainfall totals (865 and 1060 mm, respectively) well above the long-term average. This work therefore aimed to: (*i*) determine differences in SOC concentration and density in improved, native, and lightly wooded pastures on the Northern Tablelands of NSW; (*ii*) examine differences between the three land-management systems in their SOC fractions; and (*iii*) assess changes in SOC concentration and stock between the first and second sample stage, between which a significant climatic (rainfall) event had taken place.

Materials and methods

Study region

The Northern Tablelands of NSW are in the north-east of the state on a broad plateau (Fig. 1) ranging in altitude from 750 to 1200 m, with a few locations as high as 1500 m. The Northern Tablelands climate is temperate with average annual rainfall 750–800 mm, which is summer-dominant. Maximum summer temperature at all locations sampled is <30°C. Annual mean minimum temperatures are ~7°C and frosts are common from April to September (Lodge and Whalley 1989). Soils of the region vary depending on lithology but, in this study, we focussed on Chromosol soils (Isbell 2002) derived from Permian Granites that are common across the region. These soils are typically sandy in texture with free drainage but with limited inherent fertility and distinct texture-contrast profile form.

The dominant agricultural land uses across the Northern Tablelands are 'improved pasture' and 'native pasture' some with a light tree cover remaining. It is estimated that 50% of pastures on the Northern Tablelands are native (Alford *et al*. 2003), with improved perennial pastures making up around 30%. Native pastures are typically lightly fertilised or unfertilised and are dominated by native grasses such as *Microlaena*, *Poa*, and *Bothriochloa* spp., with some introduced and naturalised legumes and grasses. Improved pastures in the region comprise a range of exotic grass species, including tall fescue (*Festuca arundinacea* Schreb.), *Phalaris aquatica* L., perennial ryegrass (*Lolium perenne* L.), and cocksfoot (*Dactylis glomerata* L.) augmented by white clover (*Trifolium repens* L.), arrowleaf clover (*T. vesiculosum* Savi), and subterranean clover (*T. subterraneum* L.). Improved pastures traditionally receive a surface application of superphosphate at a rate of 250 kg ha^{-1} every 2–3 years. These native and improved pastures support a diverse range of grazing enterprises including fine wool, prime lambs, and more recently beef cattle production.

Clearing of the native woody cover of the Tablelands began in the mid-1800s and reached a peak in the 1920s–1930s. However, a significant cover remains of the original Yellow Box–Blakely's Red Gum Grassy Woodland (which has recently been declared an endangered ecological community). These open grassy woodlands (typically with a native pasture understorey) have been significantly fragmented and degraded through more than a century of human activity, but are extensively used for sheep and cattle grazing and thus comprise the third major land use of the Northern Tablelands–lightly wooded, grazed woodland (Table 1).

Sample site selection

In total, 115 sites were sampled across the Northern Tablelands region (Fig. 1), largely focussed on an area between Walcha and Glen Innes. All sampling was undertaken on Chromosols (or closely related Kurosols), on granitic parent material. Three major land-use systems were compared in order to assess their capacity to store soil carbon to 0.3 m depth: improved pasture, native pasture, and lightly wooded pasture. In stage 1, 35 sites were sampled on each of improved and native pastures, in 2009 during a period of below-average rainfall. In stage 2 (2011) in the above-average rainfall period, 15 of each of these pasture types were re-sampled and 15 lightly wooded pastures were also sampled.

Potential sites were identified from local contacts and were selected randomly. Properties were selected that fulfilled the sampling criteria (i.e. the correct soil type and land use with sufficient management records). Each landholder identified several potential paddocks that represented the nominated system and one of these paddocks was selected for sampling. Within each paddock, a site was selected that was considered to represent 'average' conditions within the paddock. Lightly

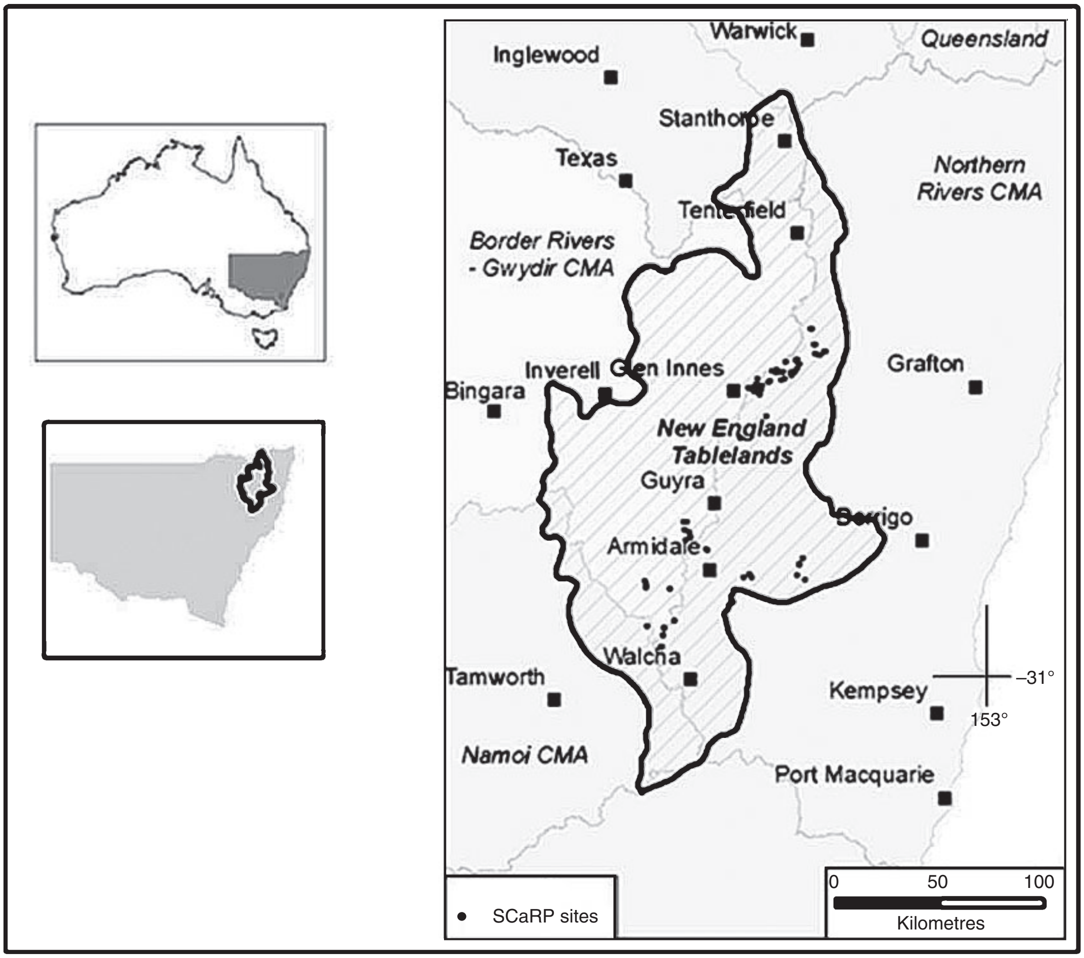

Fig. 1. Sample site locations across the Northern Tablelands of New South Wales.

Table 1. Details of land-use systems examined on the Northern Tablelands of NSW

Land use	Soil type	Land-use description	Grazing management
Introduced pasture	Chromosol	Typically, sown pastures, with regular superphosphate fertiliser history. Fertiliser applied a minimum of 5 years in the last 10. Rates vary between 6.6 and 126 kg P ha^{-1}. Usually dominated by introduced species including cocksfoot (*Dactylis glomerata*), tall fescue (*Festuca arundinacea*), perennial ryegrass (*Lolium perenne*), phalaris (*Phalaris aquatica*); clovers principally white (*Trifolium repens*) and subterranean clover (*T. subterraneum*). Generally have higher stocking rates and pasture utilisation than native pastures	Set stocking: Pastures that have been continuously grazed for at least 10 years Rotational grazing: Livestock are rotated between paddocks so that each paddock is grazed and then rested. These sites represent intensive rotational grazing (e.g. time-controlled or cell grazing) where there is a large number of paddocks per mob (>20 paddocks). Under this system, stocking pressure is high with animal grazing for 1–7 days before being rested for long periods (40–200 days). Sites had been managed in this way for >7 years
Native/naturalised pasture	Chromosol	Pastures that predominantly (>50%) comprise native pasture species including wiregrass (*Aristida ramose*), hairy panic (*Panicum effusum*), wallaby grasses (*Danthonia* spp.), which have never been cultivated or sown. Various fertiliser applications from nil to biennial up to 11 kg P ha^{-1}	Set stocking as above; Rotational grazing as above
Lightly wooded pasture	Chromosol	Predominantly native pastures (as above) on roadside reserves, travelling stock routes, and road easements. No fertiliser application recorded in the last 10 years. Light tree cover 80 stems ha^{-1} average	Regular but periodic grazing by travelling stock

wooded pasture sites were largely selected on roadside reserves, travelling stock routes, and easements where a tree cover had remained despite broad-scale clearing in the surrounding landscape.

Soil sampling

Soil sampling at each site selected was undertaken using a random Latin-square design, following a methodology similar to McKenzie *et al*. (2002), Wilson *et al*. (2008, 2010, 2011), and Chapman *et al*. (2009), and as summarised in Sanderman *et al*. (2011). A 25 by 25 m plot was established at each sampling site and was orientated north–south. At least one soil core, 50 mm in diameter, was taken from the south-west corner to a depth of 1 m, or as deep as possible. These deep soil cores were used to confirm the soil type and describe the soil profile. The soil was then classified to the Australian Soil Classification (ASC) suborder level according to Isbell (2002). Soil profile details and other landscape/landform information were entered into the NSW OEH Soil and Landscape Information System (SALIS).

The 25 by 25 m plot was subdivided into a 5 m grid giving 36 intersections from which 10 coring points were then randomly selected (Sanderman *et al*. 2011). At each sampling point, plant material and surface litter were removed to expose the mineral soil and cores were collected using a manual corer of 50 mm diameter. Soil cores were subdivided to 0–0.1, 0.1–0.2, and 0.2–0.3 m depth increments. Each core and depth increment was stored separately in a pre-labelled bag.

Sample processing

To determine field moisture, a subsample of ~50 g was taken from each individual sample. Samples were dried at 40° and subsamples were weighed and dried at 105°C for 24–48 h or until dry; all carbon values were subsequently corrected for total oven-dry weight.

For 0–0.1 m samples, the complete sample was sieved to <2 mm, whereas for the 0.1–0.2 and 0.2–0.3 m layers a subsample of ~900 g was sieved to <2 mm. After sieving, remaining large roots were removed and the air-dried weights of the <2 mm and >2 mm soil portions were recorded. A composite sample for each depth increment was created by mixing the soil from each of the 10 soil sampling points. Each composite sample was then used for chemical analysis.

Soil analyses

Bulk density

Bulk density was calculated from the mass and volume of the three selected core samples corrected for oven-dry (105°C) moisture content. Bulk density standard deviation was calculated from the three individual cores.

Soil organic carbon content

Concentration of SOC (mg g^{-1}) was measured using high-temperature oxidative combustion followed by non-dispersive infrared detection of CO_2 with an elemental analyser (LECO Corporation, St. Joseph, MI, USA) (Sanderman *et al*. 2011). Samples were fizz-tested with a few drops of 1 M hydrochloric acid (HCl) placed directly on the sample before analysis, and positive samples were analysed again with the elemental analyser after pre-treatment with sulfurous acid (H_2SO_3) as a 5–6 wt% SO_2 solution to remove inorganic carbon. The total organic carbon (TOC) density was calculated using Eqn 1:

$$CD_i = TOC_i \times GR_i \times BD_i \times D_i \times (1 - Prt) \tag{1}$$

where CD_i is the soil carbon density (Mg ha^{-1}) for each depth, which are summed to give $CD_{0\text{–}30}$; TOC_i is the soil organic carbon concentration (Mg C Mg^{-1} soil); BD_i is the moisture-corrected bulk density; GR_i is the gravel correction for depth interval i (D_i, in cm); Prt is the proportion of the land area within the sampling unit allocated to rocks and/or trees.

Soil C stock was expressed as TOC to 0.3 m depth, in Mg ha^{-1}. Stocks of TOC were then corrected for equivalent mass (TOC_{esm}, Mg ha^{-1}). To do this, the soil mass of the 0–0.3 m sample was calculated for all sites and the 10th percentile of the masses determined. The proportion of the soil mass required from the 0.2–0.3 m depth segment to achieve the target mass was applied to determine the mass of carbon included from this depth increment.

Other soil analyses

Indicative estimates of SOC fractions were undertaken using mid-infrared (MIR) spectroscopy. The MIR scans were made using ~100 mg of finely ground, air-dried soil, with MIR spectra acquired using a Thermo Nicolet 6700 FTIR spectrometer (Thermo Fisher Scientific Inc., Waltham, MA, USA) equipped with a Pike AutoDiff automated diffuse reflectance accessory (Pike Technologies, Madison, WI, USA). Each sample was scanned for 60 scans with a KBr beam-splitter and a DTGS detector, with a spectral range of 7800–400 cm^{-1} at 8 cm^{-1} resolution. Spectra were expressed in absorbance (A) units where A = log reflectance^{-1}. An initial background reference scan was made before each sample run using a silicon carbide disc assumed to have a reflectivity of 1 (100%).

The spectra from each sample were converted to GRAMS (*.SPC) format and imported into GRAMS/32 AITM/6.00 software (Thermo Fisher Scientific Inc.). An Array Basic program, 'Predict' Ver-6.0 (Janik 2006), was used to produce the predictions for POC, HUM, ROC, clay, and Al_2O_3 from individual soil spectra based upon calibration to a set of soil samples spanning a range of Australian soils (Janik and Skjemstad 1995; Janik *et al*. 1995). For the various SOC fractions (POC, HUM, and ROC), MIR predictions were made on the basis of direct spectral analysis. The separate values were not standardised to provide a total SOC value that equalled the LECO SOC value. For this reason, these values should be considered indicative only.

Additional soil parameters determined were total nitrogen (N) (by LECO), pH($CaCl_2$), extractable phosphorus (Colwell-P; Rayment and Lyons 2011), and particle size analysis by hydrometer method of Gee and Bauder (1986).

Management data

Management data for the previous 10 years were collected by survey of landholders, as outlined by Sanderman *et al*. (2011). The survey of land management practice covered crop type, yield, tillage practice, fallowing, stubble management, pasture type, stocking rate, grazing management, fertiliser (N, P, potassium (K)), other soil amendments, and hay production for each of the previous 10 years.

Climatic data

Thirty years of monthly climate data were extracted from the SILO database (www.longpaddock.qld.gov.au/silo/index.html) for each sampling site based on their latitude and longitude. Data for average monthly temperature (°C), total rainfall (mm), total evaporation (mm), average radiation ($MJ\,m^{-2}$), and average daily vapour pressure (hPa) were obtained.

Statistical analyses

In order to determine whether a significant 'time of sampling' effect existed between the two sampling periods (t_0, 2009; and t_1, 2011), an initial analysis of variance was undertaken comparing (*i*) paired values from the 15 sites that had been repeat sampled, and (*ii*) values from the 15 re-sampled sites against the entire 35 sites sampled at t_0.

A general linear model analysis of variance was then used to examine land-management and depth effect on SOC (%) and the three SOC fractions (POC, HUM, ROC) across the combined dataset with 'system' (native, lightly wooded, and improved pasture) and 'depth' (0–0.1, 0.1–0.2, and 0.2–0.3 m soil depths) as fixed factors. Post-hoc l.s.d. analysis was used to examine pair-wise comparisons. Analysis of TOC (0–0.3 m) was undertaken using a one-way analysis of variance with land-management system as the independent factor.

Normality of each dataset was determined using goodness-of-fit Q–Q Plots with Kolmogorov–Smirnov analysis of normality. The various datasets typically required natural log (SOC, TOC, POC, ROC) or square-root transformation (HUM) to meet normality assumptions for statistical analysis. Untransformed data are presented in Tables and Figures.

To examine the effects of environmental factors and other soil properties as explanatory variables influencing TOC, a correlation matrix (two-tailed) was constructed and Pearson's Product Moment correlation coefficient computed to determine significance. The relationship between parameters that were significantly correlated was tested using linear regression, with regression coefficient β and R^2 to indicate the significance and strength of the relationship, while residual *v.* prediction plots were used to test the suitability of the chosen model. All statistical analyses were completed using IBM SPSS v20 (IBM Corporation 2012).

Results

Soil organic carbon concentration and carbon density

Initial analysis indicated that there was no significant time period effect on SOC concentration ($mg\,g^{-1}$) ($P = 0.286$), either where re-sampled sites (2011, $n = 15$) were paired with the same individual initial sample sites (2009), or where re-sample data were compared with the entire initial sampling dataset ($n = 35$). For this reason, all sample sites within each land-management system examined were treated as single datasets for subsequent analysis. This was also the case for TOC ($Mg\,ha^{-1}$).

Land-management system and depth both had a significant effect on SOC concentration ($mg\,g^{-1}$) ($P = 0.012$ and $P < 0.001$, respectively). Post-hoc analysis indicated that lightly wooded pasture had a significantly lower SOC% on average than the other two systems, which were statistically similar (Table 2). Concentration of SOC declined with each successive depth increment, a pattern that was consistent between land-management types. Analysis of individual depth increments separately indicated that a significant management system effect was found only in the surface layer (0–0.1 m).

For TOC stock to 0.3 m ($Mg\,ha^{-1}$) no significant difference was detected between the three land-management systems examined. Despite the lack of significant difference between the land-management systems, there was nevertheless a wide range in TOC ($Mg\,ha^{-1}$) across the sites examined, ranging from as little as 20 $Mg\,ha^{-1}$ to >80 $Mg\,ha^{-1}$ (Fig. 2). The histogram (Fig. 2) also indicates that the distribution was skewed towards the lower end of this range.

Other soil parameters were determined that were considered to have a potential effect on SOC (Table 3). A correlation matrix was constructed to test the association of both SOC concentration ($mg\,g^{-1}$) and TOC stock ($Mg\,ha^{-1}$) with these other soil properties (Table 4). Both SOC and TOC were correlated significantly and positively with total N and Colwell-P. A significant negative correlation ($P = 0.001$) was found between pH and SOC ($mg\,g^{-1}$), although no such relationship existed overall with TOC ($Mg\,ha^{-1}$). A plot of this relationship in Fig. 3 illustrates that, although significant,

Table 2. Mean values of soil organic carbon (SOC), total organic carbon (TOC), and SOC fractions for native, improved, and lightly wooded pastures on the Northern Tablelands of NSW

Standard errors are in parentheses

System	Depth (cm)	SOC ($mg\,g^{-1}$)	TOC (0–30 cm) ($Mg\,ha^{-1}$)	MIR predicted fractions ($mg\,g^{-1}$) POC	HUM	ROC
Improved pasture	0–10	19.76 (0.82)	43.76 (2.07)	4.95 (0.33)	11.20 (0.51)	5.46 (0.26)
	10–20	9.38 (0.73)		1.23 (0.09)	6.57 (0.43)	3.10 (0.17)
	20–30	5.85 (0.53)		0.55 (0.58)	4.62 (0.37)	1.89 (0.10)
Native pasture	0–10	19.87 (0.76)	43.04 (1.70)	5.35 (0.29)	13.22 (0.55)	6.51 (0.29)
	10–20	8.96 (0.56)		1.45 (0.09)	8.07 (0.5)	3.79 (0.22)
	20–30	5.41 (0.38)		0.50 (0.06)	5.44 (0.4)	2.35 (0.14)
Lightly wooded pasture	0–10	16.41 (1.16)	36.11 (2.83)	4.20 (0.50)	9.90 (1.07)	5.01 (0.41)
	10–20	6.90 (0.76)		1.19 (0.22)	5.81 (0.84)	2.93 (0.30)
	20–30	4.62 (1.08)		0.59 (0.12)	4.68 (1.01)	2.04 (0.29)

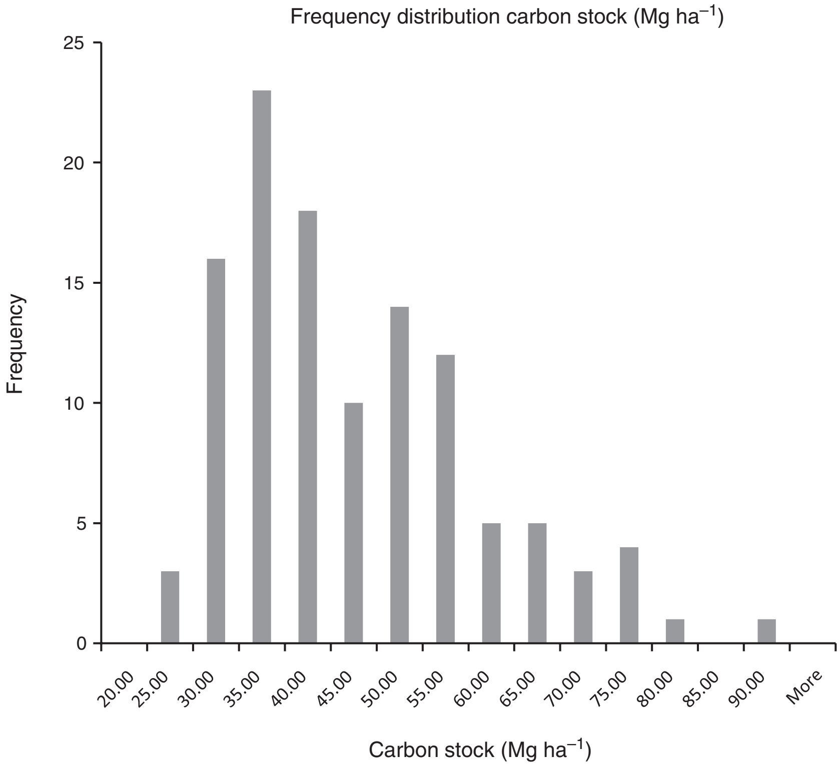

Fig. 2. Frequency distribution of total organic carbon (TOC, Mg ha^{-1}).

Table 3. Additional soil properties analysed

Standard errors are in parentheses. Within individual soil depths between land-use systems, means followed by the same letter are not significantly different at $P = 0.05$

System	Depth (cm)	pH	Measured (mg g^{-1})		MIR predicted (mg g^{-1})	
			Nitrogen	Phosphorus	Clay content	Aluminium
Improved pasture	0–10	4.74 (0.06)a	1.54 (0.07)a	35.90 (3.22)a	224.21 (10.47)a	7.47 (2.49)a
	10–20	5.28 (0.32)a	0.64 (0.04)a	13.75 (2.28)a	222.22 (10.20)a	7.74 (3.09)a
	20–30	4.94 (0.37)a	0.42 (0.04)a	7.78 (1.11)a	252.22 (12.12)a	9.66 (4.13)a
Native pasture	0–10	4.77 (0.04)a	1.54 (0.06)a	27.89 (1.93)b	245.32 (11.37)a	5.78 (3.25)b
	10–20	5.53 (0.66)a	0.66 (0.03)a	11.14 (1.21)ab	255.41 (14.03)a	7.71 (3.79)a
	20–30	5.02 (0.26)a	0.40 (0.02)a	5.99 (0.87)ab	278.69 (15.71)a	8.25 (4.65)a
Lightly wooded pasture	0–10	4.80 (0.12)a	1.08 (0.08)a	9.27 (0.72)c	252.29 (17.00)a	2.45 (4.37)a
	10–20	4.76 (0.11)a	0.52 (0.05)a	5.26 (1.19)b	265.79 (24.65)a	6.94 (8.61)a
	20–30	4.89 (0.17)a	0.40 (0.08)b	5.32 (4.89)b	317.07 (28.32)a	19.97 (13.34)a

it was not strong ($R^2 = 0.007$). Plots of total N and Colwell-P against SOC (mg g^{-1}) (Fig. 3) again illustrate significant but weak relationships ($R^2 = 0.67$ and 0.31, respectively). Analysis of residual *v.* predicted plots indicated that these simple linear models were appropriate for the analysis undertaken. No single depth increment was more strongly correlated for these properties than any other. Although few differences were found in soil pH or in contents of N, Al, or clay between the different land uses at any of the soil depths (Table 3), pairwise ANOVA of the data indicated that the Colwell-P concentration differed significantly between the three land-management systems and that the lightly wooded pastures had significantly ($P < 0.02$) lower Colwell-P concentrations than the other two systems, with improved pasture having the highest concentrations overall, and this was especially strong in the surface (0–10 cm) soil layer.

Table 4. Correlation matrix (*P*-values) of soil organic carbon (SOC, mg g^{-1}) and total organic carbon (TOC, Mg ha^{-1}) with other soil properties analysed

	TOC	pH	Total N	Colwell-P	Al	Clay
SOC	0.000	0.001	0.000	0.000	0.652	0.980
TOC	–	0.513	0.022	0.041	0.125	0.158

Of the various management data collected from the sites sampled (grazing history, fertiliser regime, etc.), no clear trends could be discerned between these factors and SOC or TOC.

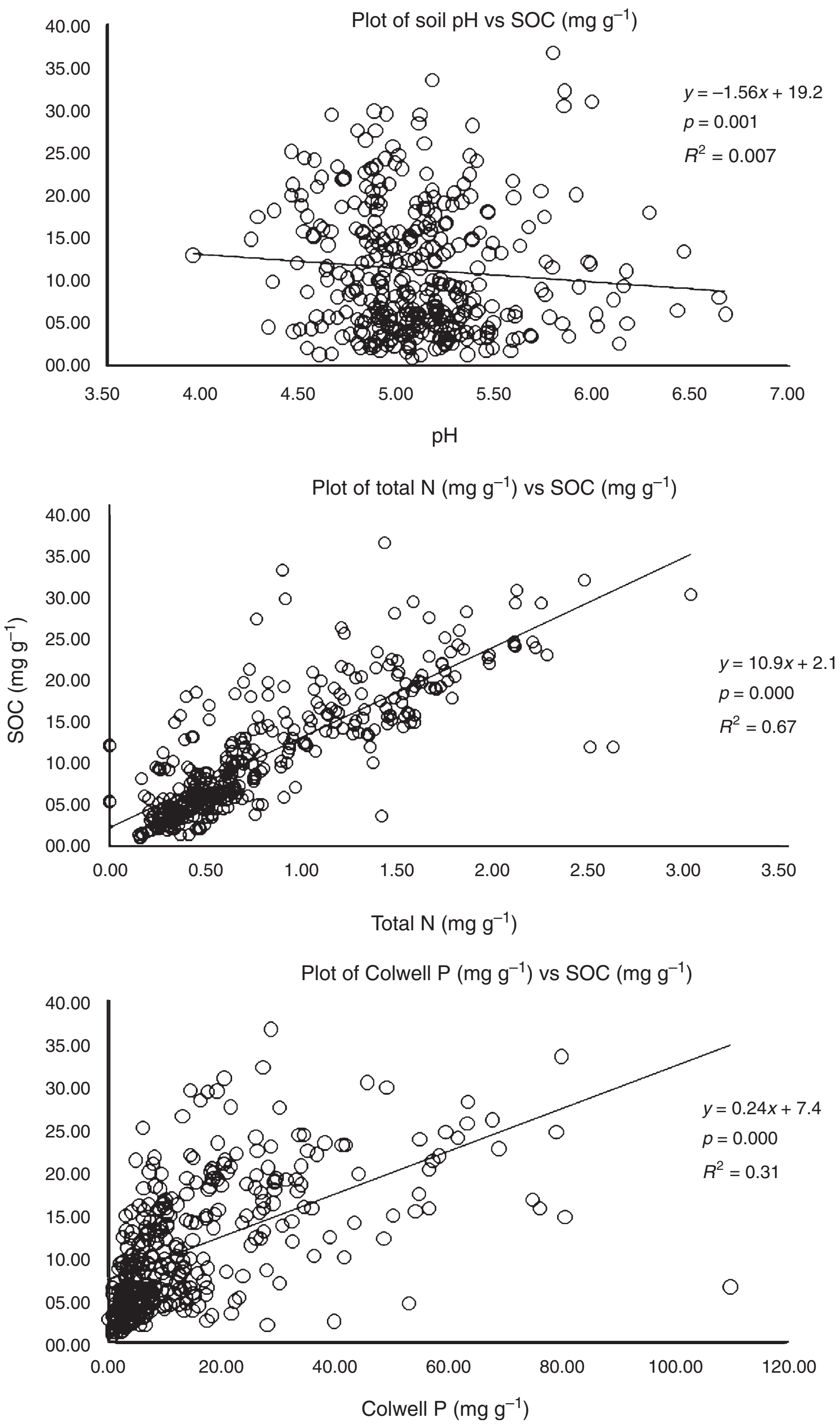

Fig. 3. Plots of pH, total N (mg g^{-1}), and Colwell-P (mg g^{-1}) *v.* soil organic carbon (SOC, mg g^{-1}).

To investigate further the nature of the variation in TOC stock across the range of sites sampled, we examined the depth distribution of SOC through the soil profile. To do this, all the sites examined were categorised, based on their TOC (Mg ha^{-1} to 30 cm), into 10 Mg ha^{-1} classes. Within each class, the average TOC in each soil layer was then computed and plotted as a continuous profile (Fig. 4*a*) and as a cumulative proportion (%) of TOC with depth (Fig. 4*b*).

From this presentation of the data, it is clear that as the total soil carbon stock class increased, the TOC in all soil layers increased and that TOC at both the surface and at depth contributed to the total. When these data were expressed as cumulative TOC with depth (Fig. 4*b*), the proportion of the TOC found in the surface soil layers progressively decreased as the TOC class increased. A consequence of this pattern is illustrated in Fig. 4*c*, which shows that SOC (mg g^{-1}) to 0.1 m is a good predictor of TOC (Mg ha^{-1}) overall but that this relationship becomes considerably less robust at higher TOC (Mg ha^{-1}) levels.

MIR-predicted SOC fractions

No significant difference was found in POC between the three land-management systems. Only soil depth was a significant factor ($P < 0.001$) in determining POC concentrations, with a significant decline with depth. Again, no land-management × depth interaction was found, indicating that this pattern was consistent across all systems. Significant land-management ($P < 0.001$) and depth ($P < 0.001$) effects were detected for the HUM fraction. This fraction again declined significantly with depth, a pattern that was consistent between the systems. Post-hoc analysis indicated that native pasture had a higher concentration of HUM than the other two systems, both of which had statistically similar concentrations of this fraction. Analysis of each soil depth independently indicated that this effect was accounted for mainly in the two near-surface soil layers (0–0.1 m, $P = 0.022$; and 0.1–0.2 m, $P = 0.029$), below which no differences existed between the soils in HUM concentration. The ROC fraction was again significantly affected by land-management system ($P < 0.001$) and soil depth ($P < 0.001$); ROC also decreased in quantity with depth in the soil, a pattern that was again consistent between the management systems. The concentration of ROC was higher in the native pasture system, with both other systems having statistically similar values. Analysis of each soil depth individually again indicated that differences in this fraction were largely accounted for in the two surface soil layers, with no difference being detected in the deeper (0.2–0.3 m) layer.

Although each fraction declined in quantity with each successive soil depth increment in line with reductions in SOC concentrations, as a proportion of the total SOC, each differed with depth in the soil. For POC, the largest proportion of the total was found in the surface (0–0.1 m) layer. For HUM and ROC, however, the proportion of the total SOC represented by these fractions increased with soil depth.

Discussion

Soil carbon variability through time in response to variable climate is widely believed to represent a significant challenge for reliable estimation and prediction of additional soil carbon storage across Australian landscapes. However, contrary to this view, we could detect no sampling-time effect across our entire dataset in either the SOC concentration (mg g^{-1}) or the TOC stock (Mg ha^{-1}). In 7 of the 10 years that preceded the first sampling period in 2009, total annual rainfall was substantially below the long-term average (BoM 2012). However, the years 2010 and 2011 both had annual rainfall totals well above the long-term average. Nevertheless, no SOC response to this climatic event could be detected across the pasture systems examined.

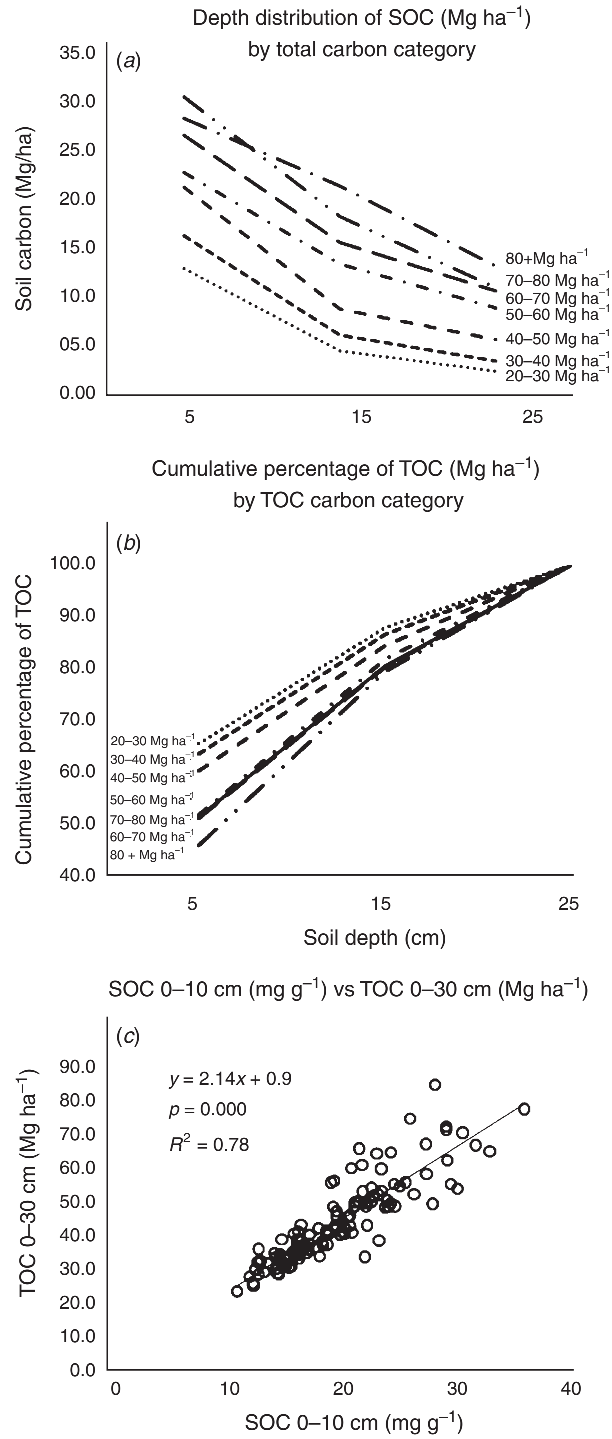

Fig. 4. Plots of total organic carbon (TOC) distribution with depth within each TOC Mg ha^{-1} class: (*a*) as a continuous plot by soil depth, (*b*) as a cumulative proportion (%) of TOC by depth, and (*c*) TOC (0–0.3 m) as a function of soil organic carbon (SOC, mg g^{-1}).

No significant difference was detected between the two principal land uses studied (improved pasture and native pasture) in either SOC concentration (mg g^{-1}) or total carbon stock (Mg ha^{-1}). This result conflicts with reviews such as Chan *et al*. (2010*a*) and Sanderman *et al*. (2010), who concluded that pasture management has the capacity to store modest but significant quantities of additional soil carbon, which suggests that improved pasture would have larger SOC quantities. Chan and McCoy (2010) also reported SOC increases under improved pastures in north-eastern NSW. The work presented by those authors was largely drawn from controlled agricultural trials and plot experiments that were subject to consistent and well-documented management actions. However, the pasture systems we examined were spread across a large spatial area and they probably contained a significant range of historical and contemporary management practices within each defined land-management system. Other, more extensive studies have also demonstrated that differences between grazing management systems across managed landscapes are not easy to detect (e.g. Wilson *et al*. 2010, 2011; Orgill *et al*. 2012). It is possible that differences in SOC imposed by pasture management do exist but that variance within the dataset made detection of such a difference difficult. Sampling to detect differences in SOC under grazing systems for carbon trading at a landscape scale is therefore likely to be challenging.

Chan *et al*. (1998) and Wilson *et al*. (2008, 2010, 2011) have also reported that where SOC differences existed between land-use systems, they were typically significant only in the surface (0–0.05 m) soil layers. It is possible, therefore, that differences did exist in SOC concentration for our sites but that the sampling method adopted for SCaRP had insufficient depth resolution to detect such changes.

Only the lightly wooded systems had lower SOC concentrations in the soil and this was largely accounted for in the surface (0–0.1 m) soil layers. This difference we attribute to the historical management of these sites. Most were drawn from roadside reserves, travelling stock routes, and road easements, land tenures that have not had a history of fertiliser application and managed grazing. These sites did in fact have significantly lower soil P and N content than the other two pasture types. This implies that fertiliser use, particularly in the improved pastures, has resulted in a higher overall SOC concentration than the unfertilised wooded pastures, which conforms with the findings of Chan *et al*. (2011), although these differences were not reflected in TOC (Mg ha^{-1}).

Despite the lack of difference between the land-use systems in total soil carbon stock, a large range of TOC (Mg ha^{-1}) values was recorded across the whole dataset. The majority of the sites we studied were at the lower end of the TOC range, implying that many sites are depleted of TOC relative to their technical storage capacity. Of the soil parameters measured, only soil N and P content were significantly (although weakly) positively correlated with both SOC concentration and TOC stock, while pH was negatively correlated with SOC only. This result confirms that, overall, there was a fertility effect on both SOC and TOC but that no real difference in fertility existed between the improved and unimproved pastures.

Work elsewhere has concluded that soil texture is a significant factor affecting total soil carbon stock (Krull *et al*. 2001). However, we found no significant correlation between soil clay content (as predicted by MIR) and either SOC or TOC, although we acknowledge a limited textural range in the soils we examined. It is likely that clay will be a significant factor only at a regional scale, between soil types and environmental domains (see Davy and Koen 2013, this issue), but will be a poor predictor within a distinct region or soil type as was the case for our sample sites.

Given the weak relationships of SOC to the range of environmental, management, and soil data collected, the wide range of values found across the landscape (~20–80 Mg ha^{-1}) is not easy to explain. Examination of the depth distribution of soil carbon suggested that sites within higher TOC classes were typically associated with a larger proportion of TOC in the deeper soil layers. Most work relating to SOC and its dynamics has focussed on the surface (0–0.3 m) layer, with the rationale that this is the most active layer of the soil and most likely to reflect management or climate induced change in SOC (e.g. Chan *et al*. 2002). However, others have pointed to the large quantity of SOC in deeper soil layers (e.g. Batjes 1996; Grace 2004) and have concluded that the distribution of carbon through the soil profile is determined by a range of factors including climate, soil type, and management (Meersmans *et al*. 2009; Baldock *et al*. 2012) and the diminishing supply of fresh organic material with soil depth (Fontaine *et al*. 2007).

Research relating to the mechanisms of SOC profile distribution indicate that SOC becomes progressively more physically and chemically protected and resistant to decomposition (Jobbágy and Jackson 2000; Six *et al*. 2002; Moni *et al*. 2010) and therefore older (Fontaine *et al*. 2007; Franzluebbers 2010) with increasing depth in the soil. Although our MIR predictions regarding soil fractions must be considered indicative only, our results appear to conform to this pattern, since POC was the dominant fraction in the surface (0–0.1 m) layer but diminished with depth, whereas the opposite trend existed for the more resistant HUM and ROC fractions. We interpret our results to mean that total soil carbon stock across these various sites studied was determined more by historical, long-term management than by short-term land-use and grazing-system type. Whether the deeper carbon resulted from ‘conservation’ of old, resistant, pre-existing carbon or had been ‘added’ as a result of long-term pasture management cannot be resolved in this work. A more detailed analysis of the nature and turnover of this carbon would go some way to elucidating the processes involved. A consequence of this result, however, is that TOC might be predicted with a high degree of confidence using the 0–10 cm SOC (mg g^{-1}) value. However, at higher TOC values, this predictive capacity became considerably weaker.

Although a significant quantity of SOC undoubtedly exists below the 0–0.3 m layer, few studies have been able to detect management impacts on SOC at these depths. We propose that the depth distribution of SOC in the 0–0.3 m soil layer might itself be an important determinant of total SOC, with older, more resistant carbon in the lower (0.1–0.3 m) layers being determined historically rather than in response to current or recent management. However, the resolution of management data is currently insufficient to resolve the causal relationships influencing this distribution, and further work is required to explain more fully the depth distribution and therefore TOC relating to these soils and management systems.

Although we have no data specifically relating to pasture dry matter production across the sites studied, from existing work relating to SOC fractions (e.g. Chan 2001; Chan *et al*. 2002; Baldock *et al*. 2012), it might be expected that higher fertiliser use and enhanced plant production of improved pastures would supply a larger quantity of POC than unimproved equivalents (Franzluebbers 2010). Indeed, POC has been reported to increase where reduced tillage is introduced on cultivated land (e.g. Chan *et al*. 2002) or where cultivated soils are converted to pasture (e.g. Conant *et al*. 2001). However, our indicative MIR results show that, although POC declined with soil depth across all our sites, we could find no significant difference in POC concentration between the three land-management systems studied. This implies that pasture systems in this region make similar contributions of POC to the soil and have similar rates of decomposition regardless of management approach, perhaps because in these systems, biomass availability is largely matched by livestock consumption.

Both HUM and ROC were found in higher concentration in the native pasture than in the other two land-use systems, and the proportion of total SOC represented by these fractions increased with soil depth. The HUM fraction represents material that is predominantly mineral-associated and has been largely modified from its original form into more stable chemical compounds that are physically protected and more resistant to decomposition (Baldock 2007; Chan *et al*. 2008). The larger HUM fraction in the native pasture soils might be explained by the nature of the pasture itself, since the amount of soil carbon in the various fractions depends on the quality of the organic matter being added to the soil. The fact that differences were detected only in the two surface layers suggests that this effect is management-induced.

The ROC is a largely inert SOC fraction with poly-aromatic structure consistent with that of charcoal (Baldock *et al*. 2012). Many Australian soils have high concentrations of charcoal because of prolonged histories of burning (Skjemstad *et al*. 1998). It might be expected that of all the SOC fractions, ROC would differ the least among the land uses. However, again, the differences that were detected were restricted to the two surface layers, and we interpret the larger concentration of ROC in these layers of the native pasture soils to be a consequence of their management history. It is possible that historically, the native pasture systems had been burnt more commonly, but our knowledge of the long-term management history on these sites is incomplete and our understanding of the dynamics of charcoal in these soils, and the effects of management on this SOC fraction, remains limited.

Conclusions

No significant difference in soil carbon stocks was detected between the two sampling times even though the first sampling was carried out during drought conditions and the second following 2 years of significantly above-average rainfall. This result suggests that detection of change in TOC need not be significantly affected by climatic (rainfall) events such as those described in our study. Although the lightly wooded pastures had lower SOC in the surface layers, we could detect no significant management effect on TOC between pasture systems, and as a result, these systems can be treated as a single management type from a carbon-storage perspective.

We have no specific data relating to pasture dry matter production and its response to above-average rainfall. Dry matter production might be expected to increase with increasing rain, but we could find no evidence of an impact of this on TOC.

A wide range of TOC values nevertheless existed across the landscape examined, but these could not be explained by climatic or environmental factors. Increasing TOC quantity across these pasture systems was, however, associated with a progressively larger proportion of subsoil carbon. We believe this subsoil carbon is conserved or accumulated through historical (rather than contemporary) management practices and resides in the soil in the more resistant (HUM and ROC) fractions.

The detection of change in TOC at landscape scale is challenging and it might not form a suitable basis for carbon accounting due to site-specific, historical, and long-term factors relating to soil management.

Acknowledgements

We gratefully acknowledge the research funding provided for this work by the Australian Department of Agriculture, Fisheries and Forestry as a component part of the national Soil Carbon Research Program. Particular thanks are due to the program leader, Dr Jeff Baldock (CSIRO) and to Dr Elizabeth Schmidt (CSIRO), for continued help and support through the project. Thanks also to the staff in the School of Environmental and Rural Science, University of New England (Frank Leayr), and the staff of the NSW Office of Environment and Heritage (Gary Sparke, Dale Higgins, Dacre King, John Lemon) for field, laboratory, and technical support. Special thanks to the army of soil processing, field, and data assistants including Yahdu Bajgai, Luke and Matt Andrews, Pema Dorji, Sangay Dorrji, Kumbu Dorji, Gopel Rizel, SangeyTshwang, Phoebe Barnes, Chris Fyfe, Jan Carruthers, Linden Burch, and Tyrone Jowett from University of New England, and Aaron Simmons from the NSW Department of Primary Industries, Orange.

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