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Soil carbon fractions and relationship to soil quality under different tillage and stubble management

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Abstract

Effect of 19 years of different tillage (direct drilled vs. conventional tillage) and stubble management (stubble retained vs. burnt) on soil carbon fractions were studied in a red earth, an Oxic Paleustalf at Wagga Wagga, NSW. The changes in carbon fractions were related to observed changes in soil structural stability and nitrogen availability. Significant differences in total organic carbon (TOC) were detected to 0.20 m depth, but the largest differences existed in the top 0.05 m where a difference of 8.0 g/kg (equivalent to 5.2 t ha^{-1}) was found between the extreme treatments (direct drilled/stubble retained (DD/SR) vs. conventional cultivation/stubble burnt (CC/SB)). Tillage had a much greater effect in reducing total carbon than stubble burning accounting for 80% of the total difference between the extreme treatments in 0–0.05 m layer. Tillage and stubble burning resulted in lower levels of different organic carbon fractions with tillage preferentially reducing the particulate organic carbon (POC) (>53 μm) (both free and associated POCs), whereas stubble burning reduced the incorporated organic carbon (<53 μm). We also found that tillage and stubble burning both significantly lowered the water stability of aggregate >2 mm, whereas stubble burning was related to the reduction of water stability of aggregates <50 μm. Furthermore, tillage was related to the decline in mineralisable nitrogen (MN) due to the loss of POC, especially the free POC fraction. POC was a more sensitive indicator of soil quality changes under different tillage and stubble management than TOC.

Keywords: Aggregate stability; Particulate organic carbon; Carbon sequestration; Conservation tillage

1. Introduction

Because of its importance to all the three aspects of soil quality, physical, chemical as well as biological (Johnston, 1986; Stevenson, 1986), maintaining satisfactory soil organic matter level is an integral component of soil management strategy. However, as soil organic matter is a heterogeneous mixture of organic substances with different composition and lability (turnover time), conceptually and for modelling of soil organic carbon dynamics, it has been convenient to partition the total carbon content of a soil into different pools (Parton et al., 1987; Jenkinson, 1990). The different forms of organic matter might have different effects on soil quality and, hence, might respond differently to a particular management practice. The challenge for soil organic matter research has been to develop reliable experimental methodology for the quantification of the different pools and to relate the different forms of soil organic matter to their functional roles in soil (Dalal and Chan, 2001).

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Such knowledge would be useful for the selection of management practices to achieve the level of the appropriate forms of soil organic matter. There has been little research on the relative effectiveness of tillage and stubble management on the levels of different forms (quality) of soil organic carbon.

Particulate organic matter (POM) was found to be the fraction preferentially lost when soils under natural pastures were converted to cropping (Cambardella and Elliott, 1992; Chan, 1997). Hence, potentially it is a more sensitive indicator of management-induced changes than total organic carbon (TOC). Importantly, there is evidence suggesting that POM is closely related to nitrogen availability of soils (Chan, 1997; Wilson et al., 2001). However, the effectiveness of tillage and stubble management on the level of POM in soils is not entirely clear.

With the recognition of the potential of using soil as a sink for carbon and, therefore, as a possible means of greenhouse gas abatement, there is an increasing interest in the mechanisms controlling sequestration of soil carbon and the management practices that encourage these mechanisms. Lal (1997) estimated that conversion of conventional to conservation tillage may lead to a global carbon sequestration of $1.5-4.9 \times 10^{15}$ g by 2020. With a better understanding of the processes involved, appropriate actions that are effective in sequestering carbon might be identified. Research on soil organic sequestration for different soil/climate/cropping systems is necessary.

This paper reports the effects of 19 years of tillage and stubble management on soil organic carbon fractions and the resulting consequences on soil quality parameters namely, soil aggregate stability and nitrogen availability.

2. Materials and methods

2.1. Experimental design

The long-term rotation/tillage experiment began in 1979 at the Wagga Wagga Agricultural Institute, Wagga Wagga (35°05′S, 147°20′E), NSW. Differences in TOC under different tillage/stubble/rotation treatments and the resulting differences in soil properties have been reported earlier (Chan et al., 1992; Heenan et al., 1995). In this paper, we were only concerned with four tillage/stubble treatments under wheat/lupin rotation, namely:

1. direct drilled and stubble retained — DD/SR,
2. direct drilled and stubble burnt — DD/SB,
3. conventional cultivation and stubble retained — CC/SR,
4. conventional cultivation and stubble burnt — CC/SB.

For the tillage treatments, DD refers to no cultivation prior to sowing and CC to three cultivations prior to sowing. Cultivation was carried out to about 0.1 m following local farmers' practice at the time namely using offset tandem disc harrows (until 1992 and thereafter scarifiers) in the SR treatments and scarifiers in the SB treatments. Stubble burning was carried out after harvest in March/April during early- to mid-autumn after fire bans were removed. Treatments were arranged in a factorial with randomised block design with six blocks. In the wheat/lupin rotation, each crop was grown on three blocks so that both crops were represented every year. Plots were $50\ \mathrm{m} \times 4.3\ \mathrm{m}$. Lime was applied over half of each plot in 1991. Further details on the design and management of treatments are available in Heenan et al. (1994).

2.2. Soil and sampling

The soil was an Oxic Paleustalf, a red earth. The soil profile was characterised by gradual transition in texture with depth. The surface A horizon (0–0.2 m) was brown to greyish brown clay loam (27% clay) which gradually changed to a light to medium reddish brown clay at about 0.2 m. The pH of the un-limed A horizon (0–0.12 m) was acid about 4.5 in 0.01 M $CaCl_2$.

In March 1998, after harvesting lupin, soil samples were collected from the un-limed half of the plots from all the four tillage/stubble treatments in the three blocks. In each plot, a composite sample was collected from four depths using a spade, namely 0–0.05, 0.05–0.10, 0.10–0.15 and 0.15–0.20 m using a narrow spade. Sampling was carried out from the side of an excavation by cutting away blocks of soil. Six sub-samples ($0.1\ \mathrm{m} \times 0.1\ \mathrm{m} \times 0.05\ \mathrm{m}$) were collected at random over the area and bulked to form the composite sample.

In the laboratory, the soil samples were air-dried at 36°C and thoroughly mixed. Roots and large pieces of litter were removed from the soil samples. Sub-samples were gently crushed to pass a 6.3 mm sieve. Sub-samples were ground to pass through 2 mm sieve.

2.3. Carbon fractionation and carbon determination

For the 0–0.05 and 0.05–0.10 m layer samples, POM was separated into two fractions, namely free POM (fPOM) and associated POM (aPOM). The aPOM refers to the fraction of POM (>53 μm) which was associated with soil aggregates as distinct from fPOM which is freely separated from soil aggregates and can be removed electrostatically. About 20 g of the <2 mm air-dried soil was weighed and fPOM was carefully removed by tweezers and electrostatic forces (created by rubbing cellophane plastic sheets on glass rods), similar to the method used by Shield and Paul (1973). Both the fPOM and the remaining soil were weighed. The latter was then subjected to the procedure of Cambardella and Elliott (1992). After shaking with 5 g l^{-1} of sodium hexa-metaphosphate solution, the suspension was passed through a 53 μm sieve to separate out the >53 μm which contained aPOM. Both the >53 and <53 μm fractions were then oven-dried, weighed and ground to <0.5 mm.

Carbon content was determined on the whole soil and the fractions using a Leco® Carbon Analyser from oven-dried finely ground (<0.5 mm) samples (Nelson and Sommers, 1982). Carbon contents of all fractions, fPOM, >53 and <53 μm soil fractions were expressed on an oven-dried soil mass basis and referred to, respectively, as fPOC, aPOC and incorporated organic carbon (IOC).

2.4. Water stable aggregation

About 20 g of the air-dried <6.3 mm soil sub-sample was weighed and wet sieved for 10 min using sieves of 2 mm and 250 μm aperture in a 2-l cylindrical container. A stroke length of 38 mm at a frequency of 30 strokes per minute was used. After the wet sieving, the container was inverted 10 times manually and the <50 μm fraction in suspension determined using pipette sampling technique. Proportions of water stable aggregates >2 mm, 2 mm–250 μm, 250–20 μm and <50 μm were calculated. All the measurements were duplicated.

2.5. Mineralisable nitrogen (MN)

MN was determined by anaerobic incubation method following Keeney (1984).

2.6. Statistical analysis

Results from the different tillage and stubble treatments were analysed using two way analysis of variance for each layer. The treatment means were compared using least significant differences for the main effects as well as their interactions. Unless otherwise stated, differences were significant at $P < 0.05$.

3. Results and discussions

3.1. TOC and fractions

Significant differences in total soil organic (TOC) amongst the different soils were found to 0.20 m (Fig. 1), however the magnitude of the differences decreased with depth. In the 0–0.05 m layer, both tillage and stubble effects were significant but not their interaction. TOC levels of the different soils were found in the order of $DD/SR > DD/SB > CC/SR > CC/SB$ with DD/SR being 8.0 g/kg higher than CC/SB. The latter difference was equivalent to 5.2 t ha^{-1} (based on a bulk density of 1.3 Mg m^{-3}). While the two DD soils had on average 40% more TOC than the two CC soils (22.1 vs. 15.8 g/kg), the corresponding difference for SR and SB was only 9.4% (19.8 vs. 18.1 g/kg). Therefore, after 19 years of treatment, tillage had much greater impact on soil organic carbon than stubble burning.

Recovery of TOC from the different fractions $(102 \pm 4\%)$ was satisfactory. For the 0–0.05 m layer, significant differences in tillage but neither stubble nor their interaction were found for fPOC as well as aPOC fractions. Both forms of particulate organic carbon (POC) were significantly higher in the DD soils compared to the CC soils with fPOC and aPOC of the DD soils 1.81 and 2.08 times, respectively, that of the corresponding CC soils (Table 1). In the case of IOC, a significant stubble effect was found in that the SR soils was higher than the SB soils. Mean IOC of SR soils was 1.13 times than that of the SB soils. For the 0.05–0.10 m layer, the results of analysis of variance were similar to those of the layer above with the

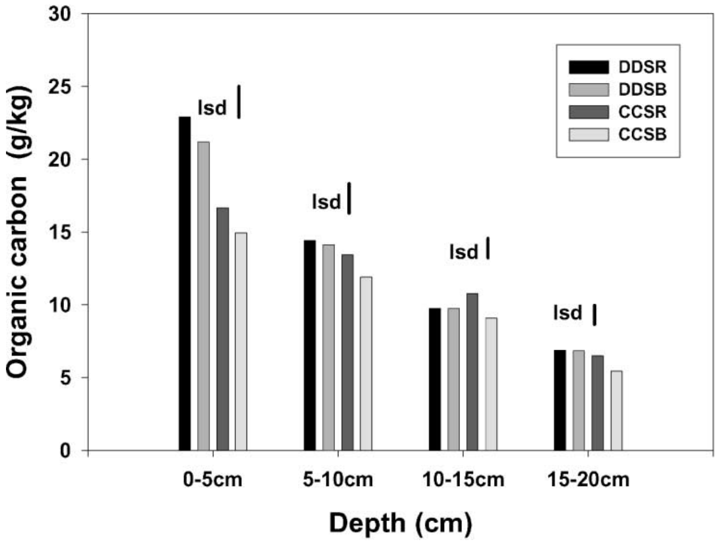

Fig. 1. TOC under different tillage and stubble management at four different depth (DD: direct drilling; CC: conventional cultivation; SR: stubble retained; SB: stubble burnt).

exception that a significant stubble effect was obtained in the case of fPOC. However, the magnitude of difference in carbon was small being only 12% that of 0–0.05 m (Table 1).

3.2. Water stable aggregation

For the 0–0.05 m layer, significant tillage as well as stubble effects were found in both direct drilling and stubble retention with significantly improved water stability of macro-aggregates >2 mm (Fig. 2). On the other hand, the percentage of <50 μm was significantly higher under stubble burning indicating a lower water stability of the micro-aggregates as a result of burning of stubble. No significant differences was detected amongst the different treatments in the other size fractions. In general, the differences in water stable aggregation amongst the different treatments

Table 1
Soil organic carbon fractions under different tillage and stubble management systems

Depth (cm)	Treatments	fPOC (g kg^{-1})[a]	aPOC (g kg^{-1})[b]	POC (g kg^{-1})[c]	IOC (g kg^{-1})[d]
0–5	DD/SR	4.3	11.0	15.3	9.6
	CC/SR	2.8	4.8	7.6	9.0
	DD/SB	5.7	8.8	14.3	8.5
	CC/SB	2.7	4.7	7.4	7.9
$LSD_{0.05}$		1.8	2.7	2.3	0.6
5–10	DD/SR	0.5	4.4	4.9	9.4
	CC/SR	0.4	3.9	4.3	9.4
	DD/SB	0.6	4.5	5.1	8.9
	CC/SB	0.7	3.3	4.0	7.9
$LSD_{0.05}$		0.2	0.6	0.3	0.5

[a] Free particulate organic carbon.
[b] Associated particulate organic carbon.
[c] POC = fPOC + aPOC.
[d] Incorporated organic carbon $< 53\,\mu m$.

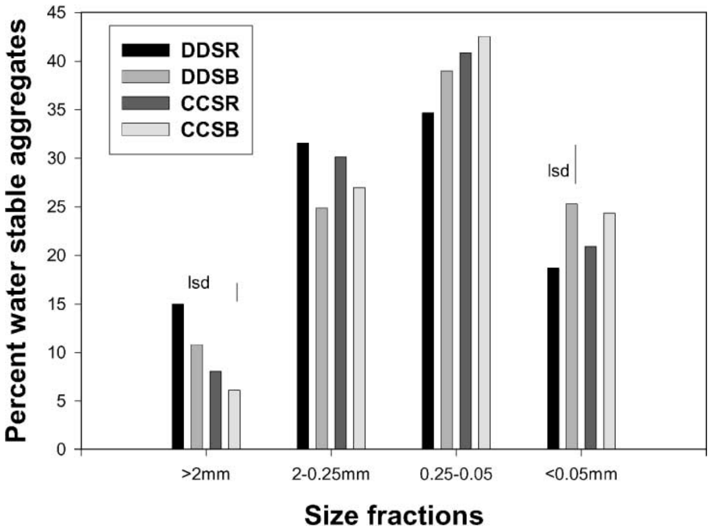

Fig. 2. Water stable aggregation under different tillage and stubble management at 0–5 cm depth (DD: direct drilling; CC: conventional cultivation; SR: stubble retained; SB: stubble burnt).

was much less in 0.05–0.10 m layer. The greatest difference was detected in the >2 mm fraction where the CC/SB soil had the lowest value (results not shown).

Correlation analyses indicated significant relationships between the level of macro-aggregate stability (>2 mm) and aPOC $(P < 0.05)$ as well as IOC $(P < 0.01)$ (Table 2). However, it was neither significantly related to fPOC nor TOC. For the <50 μm fraction, it was significantly related to IOC $(P < 0.05)$ but neither to TOC nor any of the POC fractions.

Table 2
Correlation between macro-aggregate stability (>2 mm), micro-aggregate stability (<50 μm), MN and different carbon fractions $(n = 6)$

	fPOC	aPOC	POC	IOC	TOC
>2 mm	0.289[a]	0.658[*]	0.514[a]	0.801[**]	0.553[a]
<50 μm	0.432[a]	0.039[a]	0.216[a]	−0.702[*]	0.133[a]
MN	0.935[***]	0.725[*]	0.842[**]	−0.001[a]	0.849[**]

[a] Not significantly correlated at 5%.
[*] Significantly correlated at 5%.
[**] Significantly correlated at 1%.
[***] Significantly correlated at 0.01%.

3.3. Minerisable nitrogen

MN of the 0–0.05 m layer for all the treatments was much higher than that of 0.05–0.10 m. Significant tillage effect was found for both layers in that the DD soils had significantly higher MN (Table 3).

Correlation analyses indicated that MN was most highly correlated with fPOC $(P < 0.0001)$, less so with aPOC and TOC $(P < 0.01)$ but not with IOC (Table 2). The fPOC represented the more recent carbon inputs and as lupin was the crop grown the previous season, a large proportion of the fPOC was derived from the lupin stubble and root material, thus, accounting for the high correlation between MN and fPOC.

Table 3
MN (mg/kg) under different tillage and stubble management at two depths

Treatments	0–5 cm	5–10 cm
DD/SR	87.9	19.8
CC/SR	78.3	17.3
DD/SB	105.6	19.7
CC/SB	81.9	15.8
$LSD_{tillage}$	6.3	1.1

3.4. Soil structure and carbon fractions

The present results support the hierarchical soil structure model, namely the existence of different levels of soil structure with different stabilising mechanisms (Tisdall and Oades, 1982; Dexter, 1988). From our results, stability of smaller aggregates, particularly those <50 μm was related to organic carbon <53 μm (IOC), whereas stability of the larger aggregates, namely >2 mm is affected by POC as well as IOC. According to Tisdall and Oades (1982), stability of macro-aggregates (>250 μm) is controlled by the temporary forms of organic carbon such as roots and fungal hyphae and as such is more sensitive to management practices. On the other hand, stability of micro-aggregates (<250 μm) is dependent on more persistent forms of stabilising agents such as humified organic carbon materials and sesqui-oxides and, hence, tends to be not easily changed by management practices. Our results clearly demonstrated the much greater loss of organic carbon in the form of POM as a result of tillage and suggested an association of the loss in water stability of >2 mm soil fractions with the loss of POM.

In the present investigation, burning of stubble resulted in the loss of organic carbon which was mainly in the <53 μm fraction, even though of a magnitude much less than that of POC. It is generally assumed that this fraction of organic carbon exists largely in association with mineral soil and is protected from microbial breakdown (Hassink, 1997). The latter author reported that the level of organic carbon associated with <20 μm did not change under cropping for Dutch soils. After 19 years of burning of stubble, a significant increase in breakdown of aggregates to <50 μm was observed and our results suggested an association with the loss of IOC. The mechanism of this loss is not clear but might be related to the reduction in certain forms of microbial decomposition products (detectable as IOC in the present case) caused by burning. This could occur directly because of burning or indirectly by changing the composition of micro-organisms.

3.5. Tillage and stubble management

Tillage had a much greater effect in reducing total soil organic carbon than stubble burning. It accounted for 80% of the difference in TOC in the 0–0.05 m layer between the DD and CC soils after 19 years. Importantly, tillage and stubble burning preferentially removed different organic carbon fractions. While tillage preferentially removed POC (both fPOC and aPOC), stubble burning significantly reduced incorporated organic carbon (<53 μm). As a consequence, tillage and stubble burning can both significantly lower the water stability of aggregates >2 mm whereas stubble burning was responsible for the reduction in water stability of aggregates <50 μm. These have resulted in significantly different soil structural conditions, e.g. the significantly higher hydraulic conductivity under DD/SR compared to CC/SB as reported earlier (Chan and Heenan, 1993). A continual decline instability of micro-aggregates could lead to surface structural stability problems such as crusting and hardsetting and, therefore, the long-term impact of stubble burning is of concern. Research is needed to identify the cause of the stability loss. It might be possible that by altering the conditions of burning (antecedent soil water content and temperature of burning), the loss could be minimised.

Our results also indicated that tillage was responsible for the decline in MN found under conventionally tilled soil due to the loss of POC, particularly the fPOC fraction. This fraction of organic carbon is, therefore, a good indicator of available nitrogen after a legume crop.

4. Conclusions

After 19 years of different tillage and stubble management, significant changes in TOC was detectable to 0.20 m depth. Tillage removed mainly POC which accounted for 80% of the total carbon loss. Stubble burning, on the other hand, resulted in the loss of mineral associated organic carbon (<53 μm). Loss of POC was significantly related to decline in water stability of aggregates >2 mm and nitrogen mineralisation, making it a more sensitive indicator of soil quality change than TOC.

Acknowledgements

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