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Long-term effects of soil management regimes on carbon contents and respiration rates of aggregate size fractions

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Abstract

This study investigated long-term effects of soil management on size distribution of dry-sieved aggregates in a loess soil together with their organic carbon (OC) and their respiratory activity. Soil management regimes were cropland, which was either abandoned, left bare fallow or cropped for 21 yr. Abandonment increased the abundance of macroaggregates (>2 mm) in the surface soil layer (0–10 cm) and reduced that of microaggregates (<0.25 mm) relative to Cropping, whereas the Fallow treatment reduced the abundance of macroaggregates at depths of 0–10 and 10–20 cm. All treatments yielded similar aggregate size distributions at a depth of 20–30 cm. The SOC content of aggregate size fractions in the surface soil from the Abandoned plots was greater (by 1.2–4.8 g/kg) than that of the corresponding fractions from the Cropped plots, but the opposite trend was observed in the subsurface soils. Conversely, the Fallow treatment reduced the SOC content of every aggregate size fraction. Smaller aggregates generally exhibited greater cumulative levels of C mineralization than larger ones. However, the bulk of the SOC losses from the soils via mineralization was associated with aggregates of >2 mm. Abandonment significantly increased the relative contribution of macroaggregates (>2 mm) to the overall rate of SOC loss, whereas the Fallow treatment significantly reduced the contribution of 0.25–2 mm aggregates to total SOC loss in the surface soil while substantially increasing their contribution in the subsurface soil.

Keywords: Aggregate-associated organic carbon, bare fallow, cropland abandonment, dry-sieved aggregate, soil organic carbon stability

Introduction

Soil organic carbon (SOC) is a key soil quality indicator, and increasing the sequestration of carbon in soils could potentially mitigate increases in the atmospheric levels of greenhouse gases such as carbon dioxide (CO_2) (Sainju *et al.*, 2009). Soil aggregates are the basic unit of soil structure and play central roles in SOC sequestration. They also have important effects on microbial distribution and behaviour, oxygen diffusion, water flow, run-off and erosion, as summarized by Six *et al.* (2004). All of these processes in turn have significant effects on SOC dynamics.

Aggregate size class distributions are sensitive to various aspects of soil management including land use (Noellemeyer *et al.*, 2008), tillage practices (Fernandez *et al.*, 2010) and nutrient management (Wang *et al.*, 2011). In general, reducing soil disturbance or increasing the input of organic materials increases the abundance of soil macroaggregates (>0.25 mm) and reduces that of microaggregates (<0.25 mm), thereby improving the aggregation behaviour of soil (Wang *et al.*, 2011; Kösters *et al.*, 2013). However, the relationship between aggregate size distribution and the content of soil organic carbon (SOC) is currently unclear. Reductions in SOC levels associated with decreases in aggregate size have been reported by Adesodum *et al.* (2005), Sainju *et al.* (2009) and Mandiola *et al.* (2011), but the opposite was reported by Holeplass *et al.* (2004) and Jha *et al.* (2012). Such discrepancies may stem from differences in the soils and ecosystems studied as well as differences in the climatic conditions and management histories of the sites.

The situation is further complicated by the fact that the extent of SOC mineralization in aggregates (which reflects SOC stability) is not always reported. Drury *et al.* (2004) reported that CO_2-C production increased as the relative abundance of larger aggregate size classes declined, whereas

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Noellemeyer *et al.* (2008) found that aggregates of intermediate size (1–4 mm) had the strongest respiratory CO_2 production. Razafimbelo *et al.* (2008) and Fazle Rabbi *et al.* (2014) found no significant difference in the amount of carbon mineralized in macro- and microaggregates. Conversely, Yu *et al.* (2012) reported that macroaggregates produced more CO_2 than microaggregates. These differences may be due to differences in ecosystem type, soil properties or climatic conditions, all of which are likely to have important effects on carbon mineralization processes (Marinari *et al.*, 2010).

Land abandonment and subsequent cessation of agricultural activities occur globally in all ecosystem types, as summarized by Raiesi (2012). This approach represents one way of restoring soil conditions and SOC levels after prolonged cultivation and agricultural usage (Shang *et al.*, 2014). Several studies have shown that the abandonment of agricultural fields has important effects on soil carbon stocks, carbon fractions, organic matter quality, microbial activity and biomass (Raiesi, 2012; Yang *et al.*, 2012; Shang *et al.*, 2014). However, it is not yet clear how land abandonment affects the stability of aggregates and their SOC sequestration. These issues therefore merit further investigation to better understand the dynamics of SOC following crop land abandonment. Here, we present results relating to the effects of cropland abandonment on dry aggregate distribution, SOC sequestration in aggregates and aggregate-associated SOC mineralization in a loess soil.

Materials and methods

Study site and experimental design

A long-term experiment was established in October 1990 at the Chinese National Soil Fertility and Fertilizer Efficiency Monitoring Base for Loessial Soil (N 34º 17′51″, E 108°00′48″, with an altitude of 524.7 m a.s.l.), located on levelled land, Yangling, Shaanxi, China. The soil at the site was a silt clay loam (clay 32%, silt 52% and sand 16%; Earth-cumuli-Orthic Anthrosols; Chinese Soil Taxonomy, 2001) derived from loess materials. On average, at the time of establishment the top soil (0–20 cm) at the site contained 7.44 g/kg organic C, 0.93 g/kg total N, 9.57 mg/kg Olsen P, 191 mg/kg exchangeable K, 92.5 g/kg $CaCO_3$ and had a pH of 8.62 across all plots, with little interplot variation as previously reported by Yang *et al.* (2012). The experimental site has a mean annual temperature of 13.0 °C and mean annual precipitation of ca. 550 mm, which mainly falls from June to September.

The field experiment included 11 treatments in total, three of which were considered in this work. The first of these treatments was Abandonment, in which the land was subject to no artificial perturbation and vegetation was permitted to grow naturally, causing the plots to become dominated by a diverse range of herbaceous species with a few tree species. The second treatment involved leaving the plots in a bare fallow state with no growing vegetation and no inputs of mineral fertilizer or manure; weeds were manually removed by hoeing and annual ploughing during October. The third treatment was based on a rotation of winter wheat (*Triticum aestivum* L.)–summer maize (*Zea mays* L.), with irrigation when required; an established local cropping system that provides two crops per year. These treatments are henceforth referred to as Abandonment, Fallow and Cropping, respectively. Winter wheat was sown in October and harvested in the following June, and then summer maize was planted and harvested about 3 months later at the end of September or early October. The cropping system was conventionally managed without crop residue return, using an annual inorganic fertilizer input of 352 kg/ha nitrogen (N), 82 kg/ha phosphorus (P) and 146 kg/ha potassium (K). The plot size for the cropping treatment was 14 × 14 m, while that for fallow and abandonment was 14 × 7 m.

Soil sampling and analysis

Soil samples were collected at the beginning of June 2011 just before the winter wheat harvest. Three 30 cm long soil cores with inner diameters of 10 cm were collected from each plot. The cores were divided into 10 cm segments corresponding to depths of 0–10, 10–20 and 20–30 cm, and all segments corresponding to the same depth were combined to create a composite soil sample. This process was repeated three times for each treatment so as to give three replicate composite samples for each depth.

Field-moist soil was gently broken up so that it could pass through a 10-mm sieve and then air-dried. Subsamples of 200 g were then shaken through a motorized sieving device with opening diameters of 2, 1, 0.5 and 0.25 mm for 5 min. The soil retained by each sieve and the fraction passing through the 0.25-mm sieve was weighed, after which the OC contents of each aggregate size fraction and OC and TN contents of the unfractionated soil were determined by wet combustion in a mixture of concentrated sulphuric acid containing $K_2Cr_2O_7$ and by the semi-macro-Kjeldahl method, respectively (Bao, 2005).

The respiratory activity of the bulk soil and its individual size fractions was determined by incubating 100 g samples of the nonfractionated soil and the >2 mm, 0.25–2 mm and <0.25 mm aggregate size fractions in closed vessels in an incubation chamber at 25 °C and 60% of their water holding capacity. The respired CO_2 was trapped in 0.5 N NaOH and quantified by titrating the excess NaOH with 0.4 N H_2SO_4. The CO_2 output of each sample was determined after 2-, 4-, 7-, 10-, 14-, 21-, 28-, 35- and 42-day incubation for samples collected at depths of 0–10 and 10–20 cm. Cumulative CO_2 production values were used to compare the respiratory activities of different aggregate size fractions and soils subjected to different management regimes.

Data analysis

The proportion of total SOC associated with a given aggregate fraction was calculated using the measured SOC concentration for the fraction in question (OCF_n) and the mass of the fraction (MF_n) in a given mass of unfractionated soil (SM):

$$\text{OC in aggregate}(\%) = OCF_n \times MF_n/SM \times 100 \quad (1)$$

Total respiration (TR) was calculated from the CO_2 production of each aggregate fraction (CO_2F_n) and the mass of each fraction (MF_n) in a known mass of unfractionated soil (SM):

$$TR = CO_2\,F_n \times MF_n/SM \times 100 \quad (2)$$

The rate of SOC respiration in each aggregate fraction (CRR) was calculated as the ratio of the cumulative CO_2 production (TCO_2) to the SOC content of the aggregate fraction in question:

$$CRR(\%) = TCO_2/\text{SOC content} \quad (3)$$

For each of these variables, a mean value was obtained from the results for the three composite samples, and significant differences between the means were identified using one-way analysis of variance and the least significant difference (LSD) test with a 95% confidence threshold.

Results

Distributions of aggregate size fractions

Each of the Cropping, Fallow and Abandonment treatments was associated with a different aggregate size class distribution (Fig. 1). The >2 mm class was the most abundant while the 0.25–0.5 mm or <0.25 mm classes were least abundant for all treatments and depths, suggesting that large macroaggregates comprised the bulk of the aggregates within the studied loess soils as determined by dry sieving.

At the 0–10 cm depth, aggregates with diameters of 0.5–2 mm were significantly more abundant in the Cropping soil samples than in those from the Fallow treatment. In addition, the Cropping samples had significantly greater contents of >2 mm aggregates and significantly lower contents of <2 mm aggregates than the Abandonment samples.

At the depth of 10–20 cm, the Fallow samples had very small contents of >2 mm aggregates but were much richer in 0.25–0.5 mm aggregates compared to the Cropping samples. The Abandonment and Cropping samples had similar aggregate size distributions, save that 1–2 mm aggregates were somewhat more abundant in the former (Fig. 1) . At the depth of 20–30 cm, there were no striking differences between the aggregate distributions of the different treatments.

Organic carbon and total nitrogen

After 21 yr, the bulk soil OC and TN levels differed significantly between treatments (Table 1). The Fallow treatment yielded the smallest SOC and TN contents at all depths. The Abandonment treatment produced noticeably

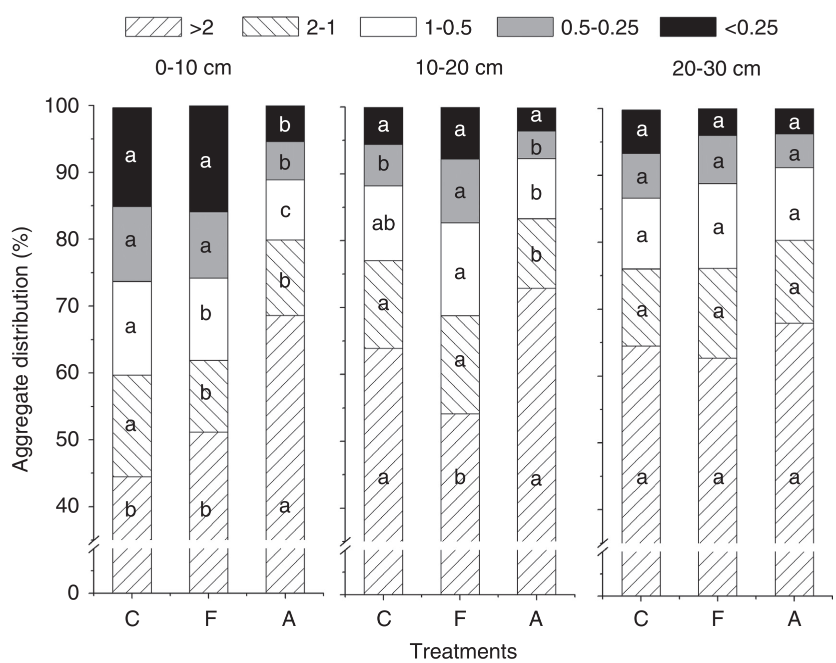

Figure 1 Distribution of dry aggregates under cropping (C), fallow (F) and abandonment (A). Different lower case letters indicate significant differences between aggregates of the same size class from different treatments at the specified soil depth ($P < 0.05$).

Table 1 Soil organic carbon and total nitrogen contents of tested soils after 21 yr (2011)

Soil depth (cm)	Treatment	SOC (g/kg)	TN (g/kg)	C:N
0–10	Cropping	11.56 b	1.43 b	8.07 a
	Fallow	10.53 c	1.30 c	8.10 a
	Abandonment	14.91 a	1.73 a	8.61 a
10–20	Cropping	8.82 a	1.11 a	7.74 a
	Fallow	7.02 c	0.92 b	7.76 a
	Abandonment	7.83 b	0.93 b	8.47 a
20–30	Cropping	6.97 a	0.73 a	9.84 a
	Fallow	5.98 b	0.65 b	9.19 a
	Abandonment	6.90 a	0.73 a	9.47 a

Different lower case letters in the same column indicate significant differences between treatments ($P < 0.05$).

greater SOC and TN levels at the 0–10 cm depth than the Cropping and Fallow regimes. At 10–20 cm depth, the Cropping treatment generated significantly higher SOC and TN levels than either Fallow or Abandonment. However, there were no differences between the C:N ratios of the various treatments at any depth.

The OC content increased as the aggregate size decreased for all treatments at depths of 0–10 and 10–20 cm, but no such trend was observed for the 20–30 cm samples (Fig. 2). In addition, the OC contents of aggregates diminished with increasing sample depth. At a depth of 0–10 cm, the largest OC concentration (across all aggregate classes) was observed in the Abandonment plots and the smallest in the Fallow plots. Conversely, for samples collected at depths of 10–20 cm, the Cropping treatment produced the greatest C contents; the OC contents for the fallow treatment were similar to those for the Abandonment regime (Fig. 2). At 20–30 cm, the OC contents of all aggregate size classes were similar across all three treatments. The sole exception was the 1–2 mm class, for which the OC content was significantly greater under Cropping than under Fallow or Abandonment.

Abandonment significantly enhanced the allocation of SOC to aggregates of >2 mm relative to that seen under Cropping (Fig. 3). The SOC distribution across aggregate size classes for the Fallow regime was similar to that for Cropping.

SOC mineralization

The level of CO_2-C respiration during the 42-day incubation periods was affected by the soil management regime and sampling depth (Fig. 4). In addition, the patterns of CO_2-C production from the unfractionated samples differed from those for the three aggregate size fractions. However, the total levels of CO_2-C production from the unfractionated samples were similar to the values calculated using Equation 1 for all of the soil management regimes ($P > 0.05$). The CO_2-C production from the 0–10 cm samples was greater than that from those collected at 10–20 cm (Fig. 4, Table 2). Across the aggregate size classes, the highest levels of C respiration were observed for the <0.25 mm fraction and the smallest values were generally observed for aggregates of >2 mm. Similar trends were observed for the rates of SOC mineralization (Fig. 5).

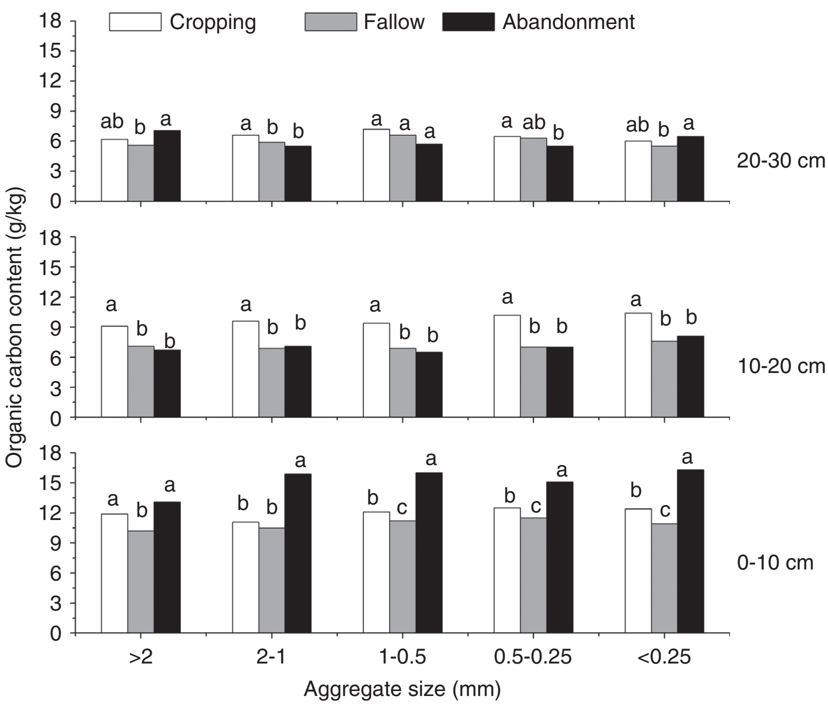

Figure 2 Carbon contents of aggregate size fractions from different soil management treatments at depths of 0–10, 10–20 and 20–30 cm. Different lower case letters indicate significant differences between aggregates of the same size class from different treatments at the specified soil depth ($P < 0.05$).

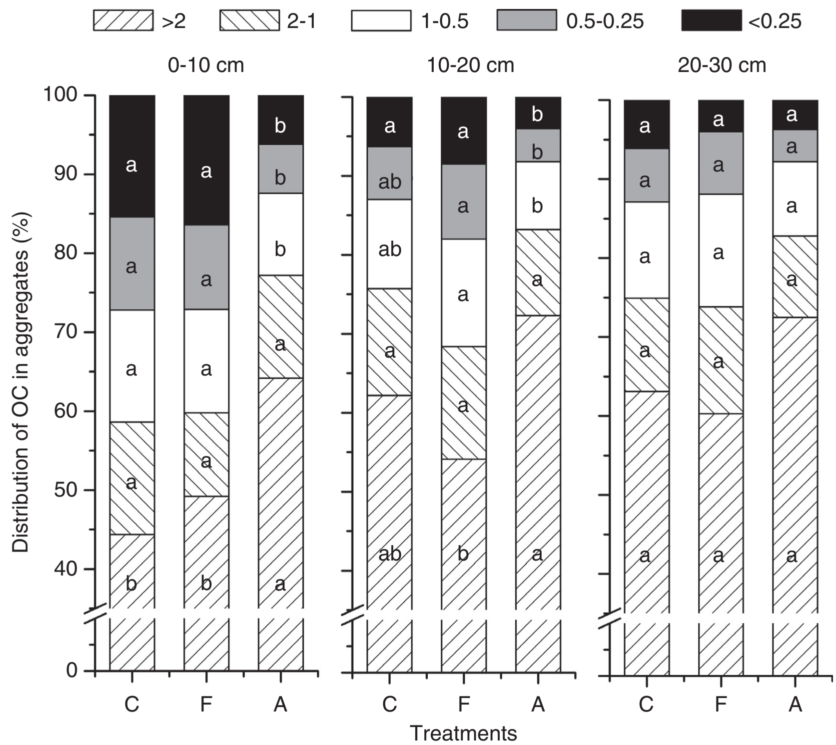

Figure 3 Distribution of soil organic carbon in aggregates collected at depths of 0–10 cm, 10–20 cm and 20–30 cm under Cropping (C), Fallow (F) and Abandonment (A). Different letters indicate significant differences between aggregates of the same size class from different treatments at the specified soil depth ($P < 0.05$).

For samples collected at 0–10 cm, the levels of respiration in aggregates of 0.2–2 and <0.25 mm from the Abandonment plots were significantly greater than those for the corresponding fractions from the Cropping and Fallow plots (Fig. 4 and Table 2). However, the SOC mineralization rates for the Abandonment and Cropping treatments were statistically indistinguishable across all aggregate size classes (Fig. 5). The samples from the Fallow plots showed substantially less respiration and rates of SOC mineralization than those from the Abandonment and Cropping plots across all aggregate size classes.

For samples collected at 10–20 cm, the 0.25–2 and <0.25 mm aggregates from the Cropping soil samples exhibited significantly greater levels of respiration than the corresponding fractions from the Fallow and Abandonment plots (Fig. 4 and Table 2). Conversely, the SOC mineralization rates for the different treatments were similar across all aggregate size classes (Fig. 5).

For the unfractionated soil samples, all of the samples from the different treatments at depths of 0–10 cm exhibited similar levels of CO_2-C production. Conversely, the unfractionated samples collected from the Fallow plots at 10–20 cm exhibited significantly lower levels of CO_2-C production than the corresponding samples from the Cropping and Abandonment treatments. The rates of SOC mineralization for unfractionated samples did not differ significantly between treatments at either depth.

The contribution of each aggregate fraction to the total CO_2-C production of the unfractionated samples over the 42-day incubation period was calculated based on the weight of each fraction per unit mass of unfractionated soil and the CO_2-C evolution from each individual fraction during incubation (Fig. 6). The >2 mm aggregate fraction contributed most to respiration for all treatments and depths; its contribution ranged from 47% in the cropping samples to 73% in the abandonment land. Conversely, the <0.25 mm aggregates contributed least for all treatments, accounting for 18% of total respiration in the Fallow samples and only 5% of that in the Abandonment samples. The relative contribution of the >2 mm aggregate size fraction in the Cropping samples was not significantly different from that in the Fallow samples, and the same was true for the <0.25 mm fractions for these two treatments. However, the relative contribution of the >2 mm aggregate size fraction in the Abandonment samples was significantly greater than that for the Cropping samples; conversely, the relative contributions of the two smaller size fractions in the Abandonment case were significantly lower than those for the equivalent fractions of the cropping samples.

Discussion

Aggregate size distribution

The treatments compared in this study had significant effects on the aggregate size distribution. Cropland abandonment for 21 yr significantly increased the relative abundance of large macroaggregates (>2 mm), and reduced the abundance

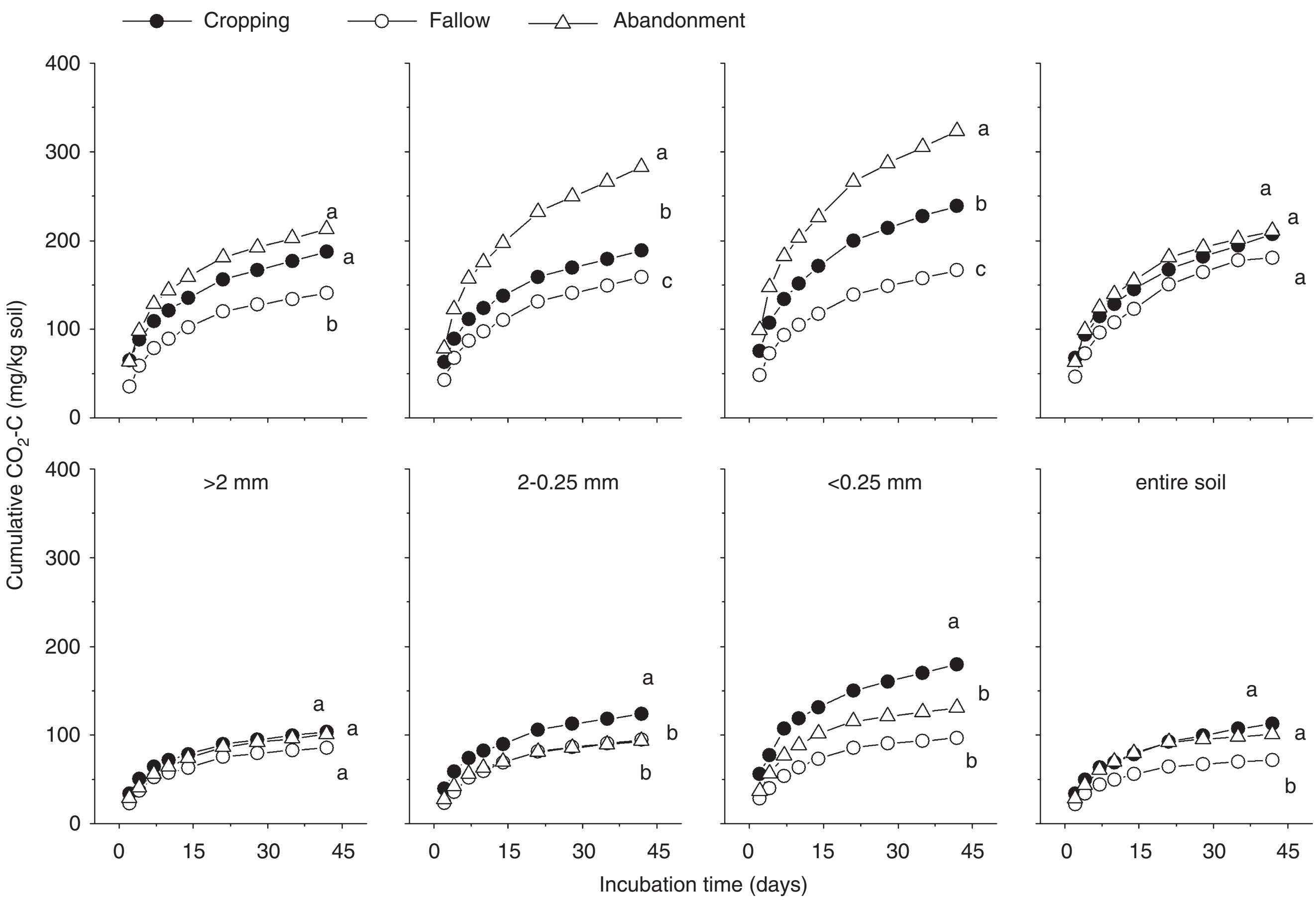

Figure 4 Respiration levels of different aggregate size fractions and unfractionated soil collected at depths of 0–10 cm (top panels) and 10–20 cm (bottom panels) from the Cropping, Fallow and Abandonment plots. Different letters indicate significant differences between treatments at $P < 0.05$.

Table 2 Cumulative CO_2 production during incubation of unfractionated soil samples and different aggregate size fractions from the cropping, fallow and abandonment plots

Soil depth (cm)	Aggregate fractions	CO_2 (mg C/kg soil)		
		Cropping	Fallow	Abandonment
0–10	Entire soil	207 bA	180 aA	211 bA
	<0.25 mm	239 aB	167 aC	323 aA
	0.25–2 mm	188 bB	159 aC	282 aA
	>2 mm	188 bA	141 aB	213 bA
10–20	Entire soil	112 bA	72 aB	101 aA
	<0.25 mm	180 aA	97 aB	130 aB
	0.25–2 mm	124 bA	95 aB	93 aB
	>2 mm	104 bA	86 aA	101 aA

Different lower case letters indicate significant differences ($P < 0.05$) between aggregate fractions. Different uppercase letters indicate significant differences ($P < 0.05$) between treatments for the same aggregate fraction.

of <2 mm aggregate fractions at a depth of 0–10 cm compared to continuous cropping over the same period. Aggregates smaller than 0.84 mm in size are known to be prone to wind erosion in semiarid dry lands (Campbell *et al*., 1993), so the greater abundance of >2 mm aggregates in Abandoned plots (relative to the Cropping and Fallow treatments) may reduce the risk of soil erosion. Our results were consistent with those of Singh & Malhi (2006), who found that the combined effects of not tilling and returning residues to the soil increased the abundance of dry macroaggregates (>2 mm) in soils of the Canadian Prairies. In the Northern Great Plains, Nichols and Toro reported that moderately grazed pastures had the greatest relative abundance of large dry macroaggregates (9.5–2 mm), whereas plots subjected to conventional tilled cropping had a greater relative abundance of smaller macroaggregates (1–0.25 mm) (Nichols & Toro, 2011). Similar results have been reported for water-stable aggregates by Kösters *et al*. (2013), who found that the reconversion of cropland into secondary pasture increased the abundance of large macroaggregates (>2 mm) and reduced that of small macroaggregates

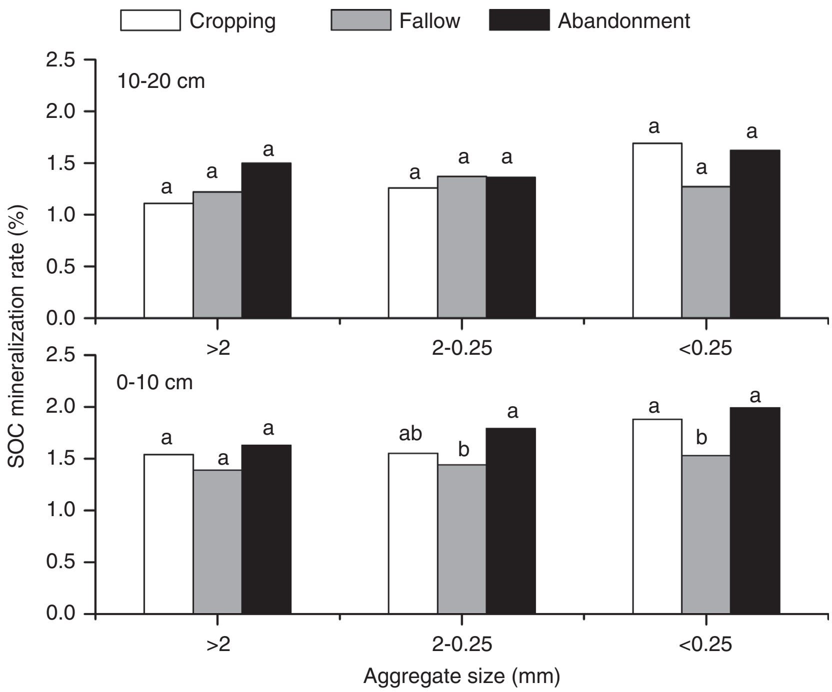

Figure 5 SOC mineralization rates for different aggregate size fractions from the Cropping, Fallow and Abandonment plots collected at depths of 0–10 cm and 10–20 cm. Different lowercase letters indicate significant differences between treatments for the specified aggregate size class ($P < 0.05$).

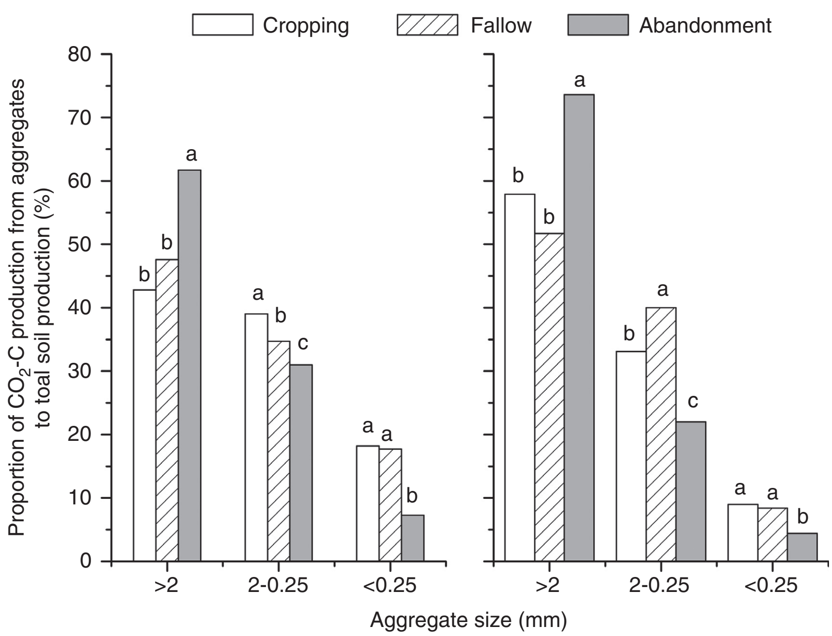

Figure 6 Contributions of individual aggregate size fractions to the total CO_2 produced over 42-day incubation by unfractionated soil samples collected at depths of 0–10 cm (left panel) and 10–20 cm (right panel). Different lowercase letters indicate significant differences between treatments for the specified aggregate size fraction ($P < 0.05$).

(0.25–2 mm) and microaggregates (<0.25 mm). Cropland abandonment thus increases soil aggregation by reducing soil disturbance and increases the organic matter content of soil together with other biological factors such as roots, fungal hyphae and by-products of microbial synthesis and decay (Tisdall & Oades, 1982; Six *et al*., 2004; Kösters *et al*., 2013). However, the differences in aggregate size distribution between the Cropping and Abandonment treatments were only observed in the topmost 10 cm of soil; this may be due to tillage transportation and the substantial input of root residues induced by the high crop yields achieved with double cropping systems using the recommended fertilizer regime (Yang *et al*., 2014).

The Fallow treatment significantly reduced the abundance of small macroaggregates (0.5–2 mm) in the topmost 10 cm of the soil and that of macroaggregates (>2 mm) at a depth of 10–20 cm. This is again consistent with the observations of Nichols & Toro (2011). These results can be explained by the need for temporary agents such as fungal hyphae, roots and polysaccharide exudates to support the binding of microaggregates into macroaggregates (Tisdall & Oades, 1982); such agents are lacking in fallow soil, so the content of macroaggregates is small.

SOC sequestration in aggregates

The content of OC generally increased with decreasing aggregate size for all treatments and depths. Similar trends with respect to OC levels have been observed for water-stable aggregates by Holeplass *et al.* (2004) and Jha *et al.* (2012). However, Sainju *et al.* (2009) reported that OC contents decreased with aggregate size in soils fractionated by dry sieving, and a similar result was obtained for water-stable aggregates in a mollisol (Mandiola *et al.*, 2011). In addition, Hurisso *et al.* (2013) found that OC contents increased with increasing water-stable aggregate size (>2, 0.25–2, 0.05–0.25 mm) under some treatments but did the opposite under others. According to Six *et al.*, there are two factors that can be used to identify the existence of an aggregate hierarchy in a soil: (i) an increase in C concentration with aggregate size and (ii) a larger content of new and more labile C (as reflected by a greater C:N ratio, among other things) in macroaggregates than in microaggregates. As such, the results obtained in our investigation and those discussed above are not consistent with the aggregate hierarchy proposed by Tisdall & Oades (1982), thereby indicating that SOC might not be the main binding agent involved in aggregate formation.

The OC contents of all aggregate size fractions were significantly greater under Abandonment than under Cropping at depths of 0–10 cm. Fernandez *et al.* (2010) similarly found that the OC concentrations of different aggregate classes were greater under a no-tilling regime than under conventional tillage. This indicates that cropland abandonment increases SOC levels in aggregates of all sizes. In conjunction with our findings on the size distribution of aggregates, these results show that the amount of OC sequestered in the macroaggregate fraction (>2 mm) under the Abandonment regime was around 20% greater than under Cropping, with a corresponding decrease in the amount of SOC sequestered in aggregates of <1 mm. This effect was primarily caused by differences in the aggregate size distribution between the two treatments (Fig. 1). However, it was only observed in the topmost soil layer. At a depth of 10–20 cm, the OC concentrations of the aggregates from the Cropping plots were significantly greater than those in samples from the Abandonment treatment. This may have been due to tillage transportation under Cropping, which would be consistent with the observed trends in the OC contents of the unfractionated soil samples (Table 1). In contrast, the distribution of SOC across aggregate size classes was similar under both the Cropping and Abandonment regimes.

The SOC contents of the Fallow soils at all depths were generally significantly less than those for the other treatments due to the lack of SOM input (Table 1) and degraded SOM reserves (Hirsch *et al.*, 2009). However, despite this depletion of SOC, the SOC distribution across aggregate size classes of the Fallow was similar to that for cropping (Fig. 3), suggesting that SOC is lost equally from all aggregate size classes under the Fallow regime.

Respiration of aggregate size fractions

The amount of CO_2-C evolved during incubation was closely related to the OC contents of the aggregate size fractions ($R^2 = 0.964$, $n = 18$, $P < 0.0001$). This implies that OC mineralization is highly sensitive to substrate availability, which is consistent with the findings of Drury *et al.* (2004), Noellemeyer *et al.* (2008) and Yu *et al.* (2012). The greater CO_2 production from smaller aggregates relative to larger ones may indicate that microbial activity was greater in these smaller aggregates, probably due to the combined effects of their greater surface area and the greater accessibility and decomposability of their carbon contents (Drury *et al.*, 2004). Our results also indicated that the SOC in large macroaggregates (>2 mm) was more stable than that in microaggregates from the Cropping and Abandonment samples. This conclusion was supported by the observation that the rate of respiration in macroaggregates of >2 mm was significantly less than that in microaggregates of <0.25 mm (Fig. 5). However, for Fallow, a depleting system, SOC stability was similar between aggregates, which may imply similar SOC property between aggregates after 21 yr of decomposition.

The Abandonment samples produced greater levels of CO_2-C than Cropping across all aggregate size classes; this trend was especially pronounced in the <0.25 and 0.25–2 mm fractions collected at 0–10 cm. However, the opposite trend was observed for samples collected at 10–20 cm (Table 2). Nevertheless, the rates of SOC mineralization in each size class from the Abandonment samples were similar to those for the corresponding aggregate fractions from the Cropping samples at both the 0–10 and 10–20 cm depths, which implies that both treatments yield similar levels of SOC stability. In general, the Fallow samples produced the smallest quantities of CO_2-C and exhibited the slowest rates of SOC mineralization for all aggregate size classes and depths, indicating that the SOC remaining in the soil of plots left fallow for 21 yr was more stable than that in Cropped or Abandoned plots. These observations further demonstrate that substrate availability has profound effects on the scope for the utilization of SOC by microorganisms. Additionally, the microbial biomass size was reduced and the microbial community structure was strongly affected in bare fallow soil (Paterson *et al.*, 2011). Whereas there were significant differences between the different treatments with respect to the CO_2-C production of specific aggregate size fractions, there were no significant differences between any of the treatments when unfractionated soil samples collected at 0–10 cm were considered, or between unfractionated samples from the Cropping and Abandonment treatments collected at 10–20 cm. This may be because some of the OC in the unfractionated samples was protected by the soil matrix, which would be disrupted during aggregate fractionation by dry sieving (Noellemeyer *et al*., 2008). Similarly, Drury *et al*. (2004) found that grinding aggregates generally enhanced their CO_2-C production.

The ratios of SOC lost via mineralization to total SOC under the Cropping, Fallow and Abandonment regimes were 1.69, 1.43 and 1.59% for surface soil and 1.29, 1.50 and 1.44% for subsurface soil, respectively; there were no significant differences between any of the treatments in either case. However, abandoning arable land or leaving it fallow for 21 yr significantly changed the contribution of different aggregate size fractions to the overall level of respiration in the soil samples (calculated using equation 2). This effect was most pronounced under the Abandonment treatment and was primarily due to changes in the aggregate distribution and the sequestration of SOC within aggregate fractions resulting from the change in the applied soil management regime.

Conclusions

Significant changes in soil aggregation and SOC sequestration were observed in the soils of plots that were abandoned or left bare for 21 yr. Abandonment favoured the formation of large macroaggregates (>2 mm) and improved OC sequestration in all aggregate size fractions at surface soil layer, whereas bare fallow caused macroaggregates (>0.5 mm) to become less abundant and stimulated OC losses from all aggregate size fractions in the topmost 20 cm. The transition from crop cultivation to bare fallow also affected the overall level of soil respiration and the contribution of different aggregate size fractions to the soil's CO_2 production. In contrast, while the transition from cultivation to abandonment did change the relative contribution of different aggregate size fractions, it did not greatly affect the overall rate of soil respiration.

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