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SHORT COMMUNICATION

The short-term cover crops increase soil labile organic carbon in southeastern Australia

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Abstract Little information is available about the effects of cover crops on soil labile organic carbon (C), especially in Australia. In this study, two cover crop species, i.e., wheat and Saia oat, were broadcast-seeded in May 2009 and then crop biomass was crimp-rolled onto the soil surface at anthesis in October 2009 in southeastern Australia. Soil and crop residue samples were taken in December 2009 to investigate the short-term effects of cover crops on soil pH, moisture, NH_4^+–N, NO_3^-–N, soluble organic C and nitrogen (N), total organic C and N, and C mineralization in comparison with a nil-crop control (CK). The soil is a Chromic Luvisol according to the FAO classification with 48.4±2.2% sand, 19.5±2.1% silt, and 32.1±2.1% clay. An exponential model fitting was employed to assess soil potentially labile organic C (C_0) and easily decomposable organic C for all treatments based on 46-day incubations. The results showed that crop residue biomass significantly decreased over the course of 2-month decomposition. The cover crop treatments had significantly higher soil pH, soluble organic C and N, cumulative CO_2–C, C_0, and easily decomposable organic C, but significantly lower NO_3^-–N than the CK. However, no significant differences were found in soil moisture, NH_4^+–N, and total organic C and N contents among the treatments. Our results indicated that the short-term cover crops increased soil labile organic C pools, which might have implications for local agricultural ecosystem managements in this region.

Keywords Cover crop · Soil organic carbon · Carbon mineralization · Labile organic carbon · Southeastern Australia

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Introduction

Growth of cover crops is an important agricultural management practice which has been widely applied to improve soil organic matter (SOM) content and, subsequently, crop productivity around the world (Sainju et al. 2008). Cover crops cannot only provide physical protection to the soil by reducing the impact of rain drops (DuPont et al. 2009) but also increase aggregation and structure (Caravaca et al. 2002) and microbial activity (Ding et al. 2006). However, little is known about the effects of short-term cover crops on soil labile organic C, especially in southeastern Australia.

Soil organic C (SOC) is considered to be a key component of SOM, which is responsible for soil functions and the sustainability of agricultural ecosystems (Chen and Xu 2008; Xu et al. 2009). Labile organic C is the most active fraction of SOC and acts as indicators of soil quality in the short term since it is sensitive to changes in management practices (Burton et al. 2010; Rovira et al.

2010). In addition, labile organic C is accessible to soil microorganisms and functions as an important short-term reservoir of nutrients for crop growth (Haynes 2005). Numerous physical and chemical methods such as hot water extraction have been used to estimate soil labile organic C (Ros et al. 2009). Some studies have shown that hot water-extractable organic C serves as an indicator of labile soil organic C (Chen et al. 2005; Jandl and Sollins 1997). However, these methods fail to identify biological properties of labile organic C fractions.

Recently, laboratory incubations in combination with modeling fitting have been widely used to characterize soil potentially labile organic C (C_0; e.g. Butterly et al. 2010; Rey and Jarvis 2006). Apart from the estimation of C_0, this method has been used to quantify easily decomposable organic C derived from C mineralization and its turnover rates based on the lability to microorganisms (von Lützow et al. 2007). The easily decomposable organic C can act as an indicator of soil labile organic C (e.g., Sainju et al. 2006).

The objectives of this study were to (1) investigate the short-term impact of cover crops (wheat and oat) on soil physical and biochemical properties and (2) assess soil labile organic C pools under cover crops in comparison with a nil-crop control (CK) in southeastern Australia. We hypothesized that cover crops improved soil labile organic C due to an input of organic matter into soils through root exudation during the growth of cover crop species and the decomposition of the large quantity of crop residues applied after crop harvest compared with the control.

Materials and methods

Experimental design

The research was conducted at the Wagga Wagga Agricultural Institute in NSW, southeastern Australia (147°20′ E, 35°05′ S). The climate in this area is temperate with mean daily maximum temperatures ranging from 12.5°C in July (midwinter) to 31.2°C in January (midsummer). The soil is a Chromic Luvisol according to the FAO classification with 48.4±2.2% sand, 19.5±2.1% silt, and 32.1±2.1% clay (Zhou et al. 2011). The study site was cropped with winter wheat in 2005 and had been fallowed prior to the experiment. Treatments included two cover crops, i.e., wheat (*Triticum aestivum*) and Saia oat (*Avena strigosa*, designated as oat), and a nil-crop control (CK). Treatments were arranged in a randomized complete block design with three replications. Each plot was 40 m^2 (4×10 m) with a rowing space of 22 cm. The cover crop species were broadcast-seeded at 80 kg ha^{-1} for wheat and oat, respectively, in late May 2009. At sowing, di-ammonia phosphate was applied at a rate of 80 kg ha^{-1} (including 20 kg N, 18 kg P, and 2–3 kg Sha^{-1}) for all plots. After crop harvest on 9 October 2009, the crop residue biomass was evenly placed on the ground within each plot to increase soil fertility until soil sampling on 9 December 2009.

Crop remaining biomass assessment and soil sampling

The aboveground biomass of each crop was measured from two random quadrats of 1 m^2 in each plot on 9 October 2009. After 2-month decomposition, the remaining crop biomass was also measured on 9 December 2009. The crop residue biomass was then combined from each plot and oven-dried at 70°C for 3 days (Zhou et al. 2010). Soil samples were collected on 9 December 2009 by taking five random cores (5 cm in diameter) to a depth of 10 cm in each plot. The five soil cores were immediately mixed thoroughly and kept in a cooler (approx. 4°C). After passing through a 2-mm sieve, the soil samples were stored at 4°C prior to analysis.

Soil physical and biochemical analyses

Soil moisture content was determined after being oven-dried at 105°C overnight. Soil pH was measured at a 1:2.5 soil/water ratio. Total soil organic C and N were determined using an Isoprime isotope ratio mass spectrometer with a Eurovector elemental analyzer (Isoprime-EuroEA 3000). Soil inorganic N and soluble organic N were measured using the method of hot water extraction (Huang et al. 2008). In brief, field moist soil samples (5 g dry weight equivalent) were incubated at 70°C with 50 mL of distilled water in a centrifuge tube overnight. The tubes were shaken on an end-to-end shaker for 1 h and filtered through a Whatman no. 42 paper, and then through a 0.45-μm filter membrane. The concentration of inorganic N was measured using a Lachat Quickchem automated analyzer (Quick Chem method 10-107-064-D for NH_4^+ and 10107-04-1-H for NO_3^- and NO_2^-). Soil soluble organic C and total soluble organic N in the soil extracts were determined using Shimadzu $TOC\text{-}_{VCPH/CPN}$ analyzer (fitted with a TN unit; Chen et al. 2004).

Measurement of soil C mineralization

Cumulative CO_2–C was calculated by a 46-day incubation protocol as described by Chen et al. (2004). Field moisture soil samples (30 g dry weight equivalent) were incubated aerobically in a 1-L sealed jar at 22°C in the dark. The CO_2 evolved from soils over the incubation period (1, 3, 6, 11, 15, 19, 26, 32, 39, and 46 days) was trapped in 0.1 M NaOH; the remaining NaOH was determined by titrating using 0.05 M HCl after precipitation of carbonate with 1 mL of 1 M $BaCl_2$. The cumulative CO_2-C was calculated

by the cumulative production of CO_2 from the soils during the 46-d incubation and expressed as mg CO_2-C kg^{-1} dry soil.

Soil potentially labile organic C

We utilized cumulative CO_2–C to evaluate the size of potentially labile organic C (C_0). Briefly, a nonlinear regression approach was used to estimate C_0 and the first-order rate constant, k (Butterly et al. 2010). The equation was $C_m = C_o \times (1 - \exp^{-kt})$, where C_m was the organic C mineralized (mg kg^{-1}) at a specific time, t. A linear regression was performed to calculate easily decomposable organic C and its decomposition rates from slopes of the segments of curves based on natural log of organic C remaining against time. The easily decomposable organic C under cover crops was expressed as percentage of SOC. The model fitting was performed using "Non-linear curve fit" program (OriginLab Corp.).

Statistical analyses

One-way analysis of variance (ANOVA) was employed to determine the effect of cover crops on soil physical and chemical properties, cumulative CO_2–C, C_0, and easily decomposable organic C compared with the CK. Correlations between soil properties and C_0 as well as easily decomposable organic C were analyzed based on Pearson correlation coefficients ($P<0.05$). The differences were considered significant at $P<0.05$. All ANOVA and correlation analyses were performed using SPSS 12.0 software (SPSS Inc., USA).

Results

Cover crop residue biomass and soil physical and biochemical properties

The wheat and oat residue biomass showed significant decreases during the course of the decomposition of cover crops. For instance, the wheat residue biomass decreased from 5,127 kg ha^{-1} after crop harvest to 3,321 kg ha^{-1} at the end of this experiment (Fig. 1).

The cover crop treatments had significantly higher soil pH and soluble organic C and N, but lower NO_3^-–N as compared with the CK (Table 1). The wheat treatment had a significantly higher C/N ratio than the oat and CK treatments. The inorganic N was predominated by NO_3^-–N across the treatments (Table 1). There were no significant differences in soil moisture, NH_4^+–N, and total soil organic C and N contents among the treatments. There were no significant differences in soil pH, moisture, NH_4^+–N, NO_3^-–N, soluble organic N, and total organic C and N contents between the wheat and oat treatments. The wheat treatment had significantly higher soil soluble organic C and C/N ratio than the oat treatment.

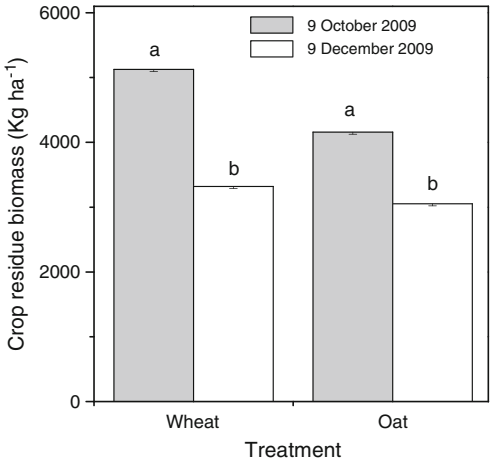

Fig. 1 Crop biomass (stem + leaves) harvested on 9 October 2009 and crop residue biomass collected on 9 December 2009 after the 2-month decomposition of cover crops applied on the ground in southeastern Australia. Data are the mean ± SE (n=3). *Different letters between bars* show significant differences at $P<0.05$

Soil C mineralization and modeling fitting

During the 46-day incubation, the cover crop treatments had significantly higher cumulative CO_2–C evolved from the soils than the CK (Fig. 2). The first-order exponential equation described well the mineralization kinetics for all the treatments (Table 2). After model fitting, the cover crop treatments had significantly higher soil potentially labile organic C (C_0) in comparison with the CK (Table 2). No significant difference in C_0 was found between the wheat and oat treatments. The first-order rate constants (k) ranged from 0.0311 to 0.0424 day^{-1} among the treatments.

Graphs were constructed by plotting the natural log of the organic C remaining against time for the treatments to identify the various phases involved in the SOC decomposition and to estimate the amounts of the easily decomposable organic C fraction (Fig. 3). The decomposition of SOC was represented by two phases: phase 1 and phase 2 (Table 2). The amounts of organic C remaining in phase 1 were considered to be easily decomposable C, which were easily available for soil microorganisms, and ranged from 2.27% (of TOC) in the CK to 2.91% in the oat treatment. The cover crop treatments had significantly higher soil easily decomposable C compared with the CK.

The relationships between soil basic properties and C_0 were analyzed among the treatments. The results showed that C_0 was significantly related to the C/N ratio (r=0.68, $P<0.05$, n=9) and soil soluble organic C (r=0.88, $P<0.01$,

Table 1 Soil physical and biochemical properties under cover crops in southeastern Australia

Treatment	pH	Moisture (%)	NH_4^+–N (mg kg^{-1})[a]	NO_3^-–N (mg kg^{-1})[a]	Soluble organic C (mg kg^{-1})[a]	Soluble organic N (mg kg^{-1})[a]	C (%)	N (%)	C/N ratio
Wheat	5.15±0.1a	6.5±0.2	10.5±0.7	36.0±2.6b	775.8±18.9a	59.4±2.2a	2.20±0.09	0.19±0.01	11.50±0.08a
Oat	5.06±0.05a	6.1±0.3	11.7±0.9	32.6±0.8b	675.6±5.9b	53.4±1.9a	2.05±0.08	0.18±0.01	11.13±0.03b
CK	4.82±0.05b	5.1±0.3	13.4±1.7	94.6±1.2a	557.9±8.8c	33.3±2.1b	2.14±0.05	0.19±0.01	10.99±0.12b

Data represent the means and standard errors (n=3). Different letters within columns show significant differences at P<0.05

[a] Concentrations of NH_4^+–N, NO_3^-–N, and soluble organic C and N were determined in the hot water extracts

n=9) and N contents (r=0.86, P<0.01, n=9). Moreover, the easily decomposable C derived from soil C mineralization was significantly related to soluble organic C (r=0.71, P< 0.05, n=9) and N contents (r=0.81, P<0.01, n=9).

Discussion

In general, crop residue biomass is applied on the ground to increase soil C storage (Coppens et al. 2006; Kaspar et al. 2006; Sainju et al. 2008). Cover crops have been found to increase soil total C in agricultural ecosystems after 3 years' application (Sainju et al. 2006). However, Kaspar et al. (2006) did not find significant increases in soil total C with oat and rye cover crops. In this study, no significant differences were found in total C and N contents among the treatments. It is difficult to detect changes in SOC over the years since SOC is not sensitive to management practices (Chen et al. 2004).

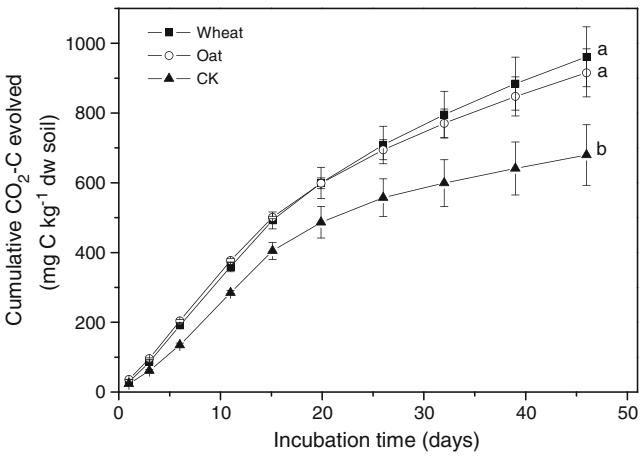

Fig. 2 Cumulative CO_2–C evolved from the soils under cover crops in southeastern Australia. Values represent the means and standard errors (n=3). *Different letters between bars* show significant differences at P<0.05

Soil soluble organic C

Different from SOC, soil labile organic C is sensitive to management practices such as cover crops and can act as a short-term reservoir of nutrients for crop growth in agricultural ecosystems (Needelman et al. 1999). The hot water extraction method has been widely used to estimate soil labile organic C (Chen et al. 2005; Jandl and Sollins 1997). Soluble organic C in the hot water extracts in this study is higher than those using the KCl (Zhou et al. 2011) and K_2SO_4 extraction methods in agricultural soils (Coppens et al. 2006). The hot water extraction method is thought to extract the soluble organic C that originates from soil microbial biomass, root exudates, and lysates (Curtin et al. 2006). Coppens et al. (2006) reported that crop residue biomass contributed to soluble organic C using ^{13}C labeling techniques in laboratory-controlled experiments. However, under field conditions, the contribution of crop residue biomass can be greatly attenuated since soluble organic C is greatly affected by many factors such as temperature and rainfall (Zhou et al. 2011). In this study, we found that cover crops increased hot water extractable organic C. This was largely associated with the microbial decomposition of large quantities of crop residues applied under the cover crops, which was evidenced by significant decreases in the remaining crop residue biomass after the 2-month decomposition (Fig. 1). No significant differences were found in most soil properties between the wheat and oat treatments, which could be attributed to similar crop species characteristics between them.

Modeling fitting of soil C mineralization

Laboratory incubation has been widely used to measure soil C mineralization since it is not influenced by root respiration and climatic variation that are encountered under field conditions (Collins et al. 2000; Davidson and Janssens 2006). Soil C mineralization is influenced by many factors such as the aboveground vegetation (Fissore et al. 2008) and soil clay content (Bell et al. 2003). In this

Table 2 Comparison of calculated potentially labile organic C (C_0) and first-order rate constants (k) as well as decomposition rate at the phases specified in the soils under cover crops

Treatment		Rate constant	Correlation	Decomposition rate at phases 1 and 2[a]		
	C_o (g Ckg^{-1})	k (day^{-1})	R^2	k_1	k_2	Easily decomposable organic C (%)[b]
Wheat	1.26a	0.0311	0.99	1.46×10^{-3}	6.05×10^{-4}	2.77±0.13a
Oat	1.13a	0.0381	0.99	1.52×10^{-3}	5.61×10^{-4}	2.91±0.11a
CK	0.79b	0.0424	0.99	1.22×10^{-3}	2.93×10^{-4}	2.27±0.05b

Different letters within columns show significant differences at $P<0.05$

[a] The decomposition rate at phases 1 and 2 was represented by k_1 and k_2, respectively

[b] Easily decomposable organic C was represented by the ratios of organic C loss at phase 1 to total soil organic C

study, the experimental site has experienced the same land uses prior to the experiment. Thus, we assume that the differences in soil C mineralization are the result of the cover crops applied, which is supported by the significantly higher cumulative CO_2–C during the incubation (Fig. 2) and potentially soil labile organic C (C_0) (Table 2) based on model fitting under the cover crops.

Compared with the resistant SOC fraction which can be stabilized by soil clay (Jastrow et al. 2007), the easily decomposable organic C is more accessible to soil microorganisms and decomposed rapidly under favorable incubation conditions (Haynes 2005). The contents of easily decomposable organic C can be determined by natural log of organic C remaining against the time to discriminate between different SOC fractions. Sainju et al. (2006) used easily decomposable C derived from 10-day incubations to indicate soil labile organic C, but did not find significant differences under cover crops, with the exception of a rye cover crop. However, we found that there was significantly higher easily decomposable organic C under the cover crops (Table 2), which might indicate that the quantification of easily decomposable organic C was a prerequisite to compare differences in this C fraction between the treatments.

It is interesting to note that the resistant SOC fraction had a lower rate constant in the CK than in the cover crop treatments, indicating that this C fraction had a higher mean residence time and slower turnover rate in the CK (inverse to rate constant). This suggests that fresh C addition derived from the cover crops applied to some extent can improve the turnover rates of the resistant SOC fraction. Further research need to be carried out to determine the contents of soil resistant C using chemical methods and the differences in temperature sensitivity between the treatments (Rey and Jarvis 2006).

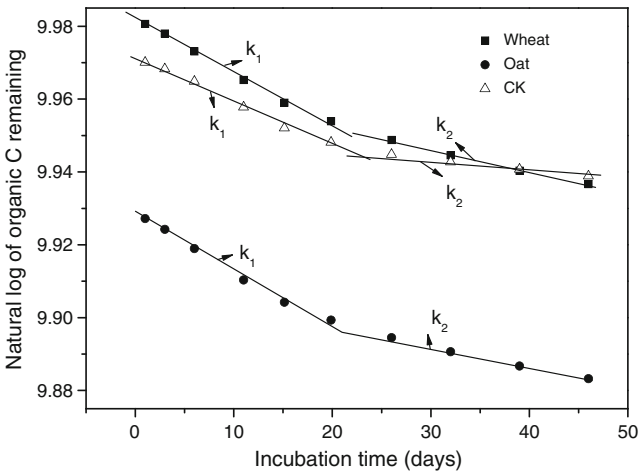

Fig. 3 Natural log of organic C remaining as a function of time in the soils under cover crops

Conclusions

The short-term use of cover cereals (wheat and oat) significantly increased soil pH, soluble organic C and N as well as cumulative CO_2–C, but lowered NO_3^-–N as compared with the CK. Model fitting analyses indicated that the cover crop treatments had significantly higher soil potentially labile organic C and easily decomposable organic C compared with the CK. Our results suggest that the short-term cover crops increase soil labile organic C, which may have implications for local agricultural ecosystem managements in this region.

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