SOIL CARBON STORAGE IN IRRIGATED COTTON CROPPING SYSTEMS SOWN ON PERMANENT BEDS

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Abstract

Long-term studies of soil organic carbon dynamics in irrigated cotton -based cropping systems under varying stubble management practices in cracking clays are relatively few. Our objective was to quantify soil organic carbon dynamics during a 9-year period in four irrigated cotton-based cropping systems sown on permanent beds in a cracking clay with subsoil sodicity near Narrabri in north-western NSW. The experimental treatments were: cotton-cotton (CC), cotton-vetch (CV), cotton-wheat where wheat stubble was incorporated (CW), and cotton-wheat-vetch where wheat stubble was retained as standing stubble (CVW). Vetch was terminated during or just prior to flowering by a combination of mowing and contact herbicides, and the residues retained as mulch. Average carbon storage in the 0-0.3 m and 0-1.2 m depths was higher when vetch was part of the crop rotation with similar values occurring in CWV and CV. On average, cropping systems that included vetch stored 2.3 t C/ha more in the 0-0.3 m depth and 5.3 t C/ha more in the 0-1.2 m depth than those that did not. These differences correspond to inputs of nutrient-rich biomass. Net carbon sequestration rates did not differ among cropping systems and did not change significantly with time in the 0-0.3 m depth but net losses occurred in the 0-1.2 m depth.

Introduction

Enhancing storage of carbon in agricultural soil has been proposed as a partial solution to offset the accelerated release of greenhouse gases associated with global warming. Under semi-arid conditions, however, significant and sustained sequestration of carbon has been reported primarily for farming systems with perennial crops and pastures (Luo *et al.*, 2009; Sanderman *et al.*, 2010). Although results from cotton (*Gossypium hirsutum* L.)-based farming systems in Australia are few, long-term studies suggest a net loss rather than sequestration of carbon in soil (Hulugalle, 2000; Hulugalle and Scott, 2008; Knowles and Singh, 2003; Odeh, 2000, unpublished data). Nonetheless, because of the high aggregation potential of clayey soils (Six *et al.*, 2002), it is theoretically possible that with conservation farming practices such as permanent beds, stubble retention/mulching and crop rotation, carbon sequestration could take place at higher rates than in non-swelling soils. The objective of this study was to quantify soil organic carbon dynamics in four irrigated cotton-based cropping systems sown on permanent beds in a cracking clay with subsoil sodicity.

Materials and methods

The experiment was located at the Australian Cotton Research Institute, near Narrabri (149°47'E, 30°13'S) in New South Wales, Australia. Soil at the experimental site is a cracking clay with an average clay content of 64% y, silt content of 11% and sand content of 25%. Exchangeable sodium percentage (ESP) during September 2002 in the 0.6-1.2 m depth was 12 and for the surface 0.6 m averaged 4.

Treatments consisted of four cotton-based rotation systems sown on permanent beds: cotton-cotton (summer cotton-winter fallow-summer cotton) (CC), cotton-vetch (summer cotton-winter vetch (*Vicia* spp.)-summer cotton) (CV), cotton-wheat (*Triticum aestivum* L.)(summer cotton-winter wheat-summer and winter fallow-summer cotton) where wheat stubble was incorporated into the beds with 1 or 2 passes of a disc-hiller (CW), and cotton-wheat-vetch (summer cotton-winter wheat-summer fallow-autumn and winter vetch-summer cotton) where wheat stubble was retained as standing stubble into which the following vetch crop was sown (CWV). Vetch was killed during or just prior to flowering through a combination of mowing and contact herbicides as previously described by Hulugalle *et al.* (2012a), and the residues retained as mulch into which the following cotton was sown. The experiment was laid out as a randomized complete block with three replications and designed such that both cotton and rotation crop phases in cotton-wheat and cotton-wheat vetch sequences were sown every year. Individual plots were 165 m long and 20 rows wide. The rows (beds) were spaced at 1-m intervals with vehicular traffic being restricted to the furrows.

Roundup-Ready® cotton (*cv*. SICALA V2RR) was sown during October from 2002 to 2005, and Bollgard® II-Roundup-Ready®-Flex® cotton thereafter (SICOT 43BRF during 2006-07, SICOT 60BRF during 2007-08 and 2008-09, and SICOT 71BRF during 2009-10 and 2010-11). Namoi woolly pod vetch was sown in the experiment from 2002 to 2006 and purple or Popany vetch thereafter. Cotton in rotations that did not include a vetch component (cotton monoculture and cotton-wheat) received N as anhydrous ammonia injected before sowing cotton until the 2008-09 season, and as urea broadcast after sowing cotton. Cotton in rotations that included vetch were not fertilised before sowing cotton but received supplementary N broadcast as urea in December or January. Application rates were dependant on N content of the vetch biomass and estimated losses. All crops were furrow irrigated at a rate of 1 ML/ha (= 100 mm) of water when rainfall was insufficient to meet evaporative demand. Cotton was picked during late April or early May with a 2-row picker after defoliation in early April. After cotton-picking, the cotton was slashed and incorporated into the beds with a "go-devil" (to facilitate pupae destruction). Wheat was sown during late May or early June and harvested during late November or early December. Vetch in CWV was sown into wheat stubble during autumn following summer rains (any time between late February and early May), and that in CV, after cotton picking and pupae-busting during May or early June. Vetch in CWV was slashed and killed with a contact herbicide usually during July or August and that in CV during September. Dry matter production of cotton prior to defoliation, wheat prior to harvest, and vetch prior to termination from 2007 to 2011 was estimated by sub-sampling from 3 locations (1 m^2) in each plot.

Soil was sampled from beds prior to planting cotton each year from September 2002 to October 2011 except during 2003 and 2004. This was done to enable at least one cropping cycle to be completed in all treatments. Soil cores (50 mm diameter) were extracted from the 0-0.1 m, 0.1-0.3 m, 0.3-0.6 m and 0.6-1.2 m depths. Air-dried soil was passed through a 0.5 mm-sieve and total soil organic carbon (SOC) concentration determined by the wet oxidation method of Walkley and Black (Rayment and Lyons, 2011). Bulk density of soil clods extracted from the cores were determined after coating in paraffin wax and displacement in water (Cresswell and Hamilton, 2002). In the 0-0.1 m depth, densityof of aggregates (1 to 10 mm diameter) was determined with the kerosene saturation method (McIntyre and Stirk, 1954). Bulk density for the 0-0.1 m depth was expressed as a weighted mean of the bulk densities of aggregates and clods (67:33 aggregates: clods) (Hulugalle and Entwistle, 1997). Soil organic carbon storage ("stocks") in any one depth was estimated by as the product of bulk density, sampling depth interval and soil organic carbon concentration. Soil organic carbon storage was reported as that in the 0-0.3 m depth (sum of storage in the 0-0.10 m and 0.10-0.30 m depths) and that in the 0-1.2 m depth (sum of storage in all depths sampled).

Results and discussion

Dry matter production and carbon inputs to soil

Dry matter production during the vetch phase of the CWV was always greater; on average more than 250% times than that in CV (Table 1). This may be due to differences in the length of growing season (5-6 months for the vetch in CWV and 3-4 months for that in CV), in-crop rainfall and soil water storage. Wheat dry matter did not differ significantly between CW and CWV. Except during the 2010-11 season, cotton dry matter yields were highest in CW. This may be associated with better soil water storage and nutrient balance, and lower compaction in CW relative to the other cropping systems. When all crops in the cropping systems were accounted for, however, above-ground dry matter production and carbon inputs to soil were generally in the order of CWV > CW > CV > CC. The 2008-09 cotton season was an exception in that total dry matter produced by CV was greater than that by CW. Assuming that soil carbon sequestration rate was of the order of 5% (the literature proposes values ranging between 3 and 15% of plant inputs from fertilised crop residues), carbon sequestered by above-ground dry matter inputs thus, averaged 0.10 t C/ha/year with CC, 0.14 C/ha/year with CV, 0.17 C/ha/year with CW, and 0.23 C/ha/year with CWV. With respect to inputs by roots (to a depth of 1.0 m), average carbon inputs to soil by cotton roots in this site were 1.41 t C/ha/year with CC, 1.26 t C/ha/year with CV, 1.68 t C/ha/year with CW and 1.37 t C/ha/year with CWV (Hulugalle *et al*., 2009). Making the same assumptions as before, C sequestered on average by cotton roots would have been of the order of 0.07 t C/ha/year with CC, 0.06 t C/ha/year with CV, 0.08 t C/ha/year with CW and 0.07 t C/ha/year with CWV. Hulugalle *et al*. (2012b) also noted that average carbon sequestration rates by rotation crops' roots were 0.10 t C/ha year with vetch in CV, 0.08 t C/ha/year with wheat in CW and 0.34 t C/ha year with wheat and vetch in CWV. Estimated average carbon sequestration rates from both above- and belowground inputs (cotton and rotation crops) were therefore, of the order of 0.17 t C/ha/year with CC, 0.30 t C/ha/year with CV, 0.33 t C/ha/year with CW and 0.64 t C/ha/year with CW. The values in CC, CV and CW are comparable to those reported by Potter (2010) for no-tilled row crops in cracking clays from Texas and that for CWV to pasture systems in the same soil type.

Soil carbon storage and sequestration

Soil carbon storage in both the 0-0.3 m and 0-1.2 m depths varied significantly among years and was significantly higher when vetch was included in the rotation (Fig. 1). Mean carbon storage in CV, CC, CW and CWV was 37.0 t C/ha, 34.6 t C/ha, 35.2 t C/ha and 37.3 t C/ha, respectively in the 0-0.3 m depth, and 119.1 t C/ha, 111.0 t C/ha, 116.0 t C/ha and 118.4 t C/ha, respectively, in the 0-1.2 m depth. On average cropping systems that included vetch stored 2.3 t C/ha more in the 0-0.3 m depth and 5.3 t C/ha more in the 0-1.2 m depth. These differences do not correspond to estimated sequestration rates and biomass inputs, which were in the order of CWV >> CW ~ CV > CC. Instead, they correspond to inputs of nutrient (i.e. nitrogen-rich) biomass.

One mechanism of soil carbon sequestration is through protection of organic matter within soil aggregates (Six *et al.*, 2002). Thus, enhancing aggregate formation and stabilisation ultimately improves carbon sequestration in soil. Processes that enhance aggregation and their stabilisation in cracking clays are an increased frequency and intensity of wet/dry cycles (Sarmah *et al*., 1996) and increased microbial, particularly fungal, activity (Tisdall *et al*., 1994). Including vetch in cropping systems significantly reduced the fallow period from 11 months in CW and 6 months in CC to 2-3 months in CWV and 3-6 weeks in CV. Thus frequency of wet/dry cycles was increased when vetch was part of the rotation. In addition, Coleman *et al*. (2010) reported that including vetch in rotations in this site, and retention and mulching of vetch residues significantly increased microbial activity and populations. They ascribed this to increased availability of unprotected micro-sites by vetch residues and enhancement of N stocks by the leguminous vetch. McLean (2009) also reported that concentrations of labile P and total P were greater in CWV than in CW and CC. Improved availability of nutrients is known to enhance microbial activity, and thus, sequestration of carbon in soils (Kirkby *et al*., 2011).

In addition to the above, cropping systems that reduce losses of previously- sequestered carbon may further enhance net sequestration. Although there are few data on soil carbon losses through erosion processes in furrow irrigated Australian cracking clays, results from the United States suggest that losses could be of the order of 0.02 to 0.05 t C/ha/year (King *et al*., 2009). If similar rates of loss were to occur in cotton fields, then the proportions of sequestered carbon removed by erosion and runoff (based on biomass inputs in this study) could range between 5 and 20%. Retention of crop residues as mulch in furrow-irrigated soils is reported to reduce erosion, and thus, carbon losses (Hulugalle and Daniells, 2005). The higher soil carbon stored in CV and CWV may, thus, partly be related to stubble retention.

Net carbon sequestration rates in the 0-0.3 m and in the 0-1.2 m depths did not differ significantly among cropping systems. Pooled results for the 0-0.3 m depth indicated that net carbon sequestration rate did not change significantly with time and was of the order of 0.004±0.21 t C/ha/year whereas this decreased at a rate of 1.60±0.69 t C/ha/year in the 0-1.2 m depth (Fig. 4). The previously estimated values of carbon sequestered from biomass inputs suggest, however, that a net increase should have occurred with time in this study. It may be that the value of 5% used to estimate carbon sequestration from biomass inputs was an overestimate for this site or that post-sequestration losses either as dissolved carbon or transported sediments in runoff, erosion and deep drainage were high. A further confounding factor is that the amounts of carbon carried into the field with irrigation water may have been significant (King *et al*., 2009).

Conclusions

Average measured carbon storage in the 0-0.3 m and 0-1.2 m depths were higher when vetch was part of the crop rotation with similar values occurring in CWV and CV. These differences do not correspond to estimated carbon sequestration rates based on biomass quantity alone, but to inputs of nutrient-rich (nitrogen) biomass. The discrepancy between measured and estimated values of sequestered carbon suggests that either the value of 5% used to estimate carbon sequestration from biomass inputs was an overestimate for this site or post-sequestration losses were high. Net carbon sequestration rates did not differ among cropping systems and did not change significantly with time in the 0-0.3 m depth but net losses occurred in the 0-1.2 m soil layer. The latter has been rarely investigated in Australian cracking clays. Future research efforts should aim to quantify the magnitude of these losses.

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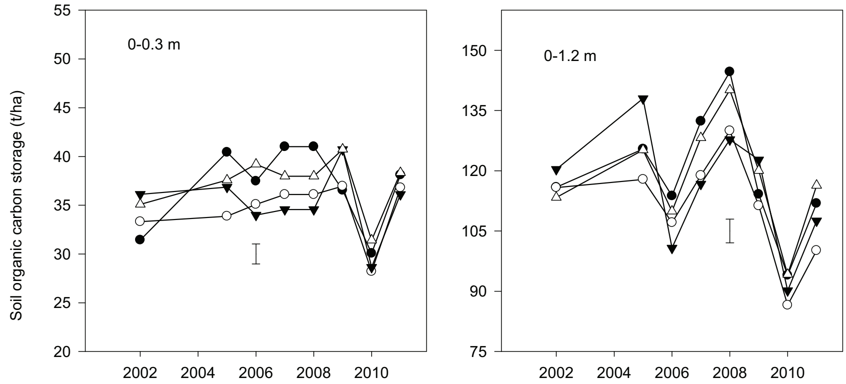

Fig. 1. Effect of cropping system on variation of soil organic carbon storage with time in the 0-0.3 m and 0-1.2 m depths. ●, cotton-vetch (CV); ○ , cotton-cotton (CC); ▼ , cotton-wheat (CW); ∆, cotton-wheat-vetch (CVW). Vertical bar is standard error of the mean (year x cropping system).

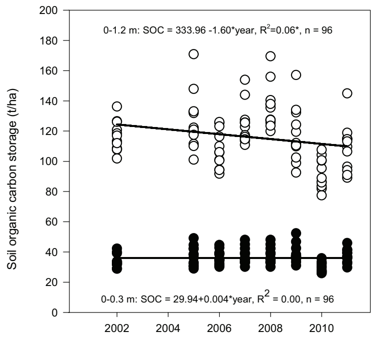

Fig. 2. Soil organic carbon sequestration (2002 to 2011) in the 0-0.3 m and 0-1.2 m depths. ●, 0-0.3 m; ○ , 0-1.2 m. Lines were fitted by linear regression to pooled data.

Table 1. Above-ground dry matter production (t/ha) of vetch, wheat and cotton from 2007 to 2011. Wheat dry matter yields are those from previous winter; thus for 2008-09 season, wheat dry matter yields shown are from 2007 winter. DM, dry matter; V, vetch; W, wheat; Cot, cotton; 40% of plant dry matter was assumed to consist of C.

Cropping system	V DM	W DM	Cot DM	Total DM	Total C	V DM	W DM	Cot DM	Total DM	Total C
	2007-08					2008-09				
Cotton-vetch	1.7	-	5.0	6.7	2.7	3.4	-	4.5	7.7	3.1
Cotton-cotton	-	-	5.1	5.1	2.0	-	-	5.4	5.4	2.2
Cotton-wheat	-	1.6[1]	7.9	9.5	3.8	-	1.0	6.2	7.2	2.9
Cotton-wheat-vetch	3.2	1.6[1]	6.3	11.1	4.4	4.2	1.1	4.7	10.0	4.0
SEM	0.16	-	0.28			0.21	0.15	0.36		
P <	0.001	-	0.01			0.01	ns	0.05		
	2009-10					2010-11				
Cotton-vetch	2.7	-	4.0	6.7	2.7	2.9	-	4.7	7.6	3.0
Cotton-cotton	-	-	4.8	4.8	1.9	-	-	4.5	4.5	1.8
Cotton-wheat	-	2.7	5.4	8.1	3.2	-	3.0	5.3	8.3	3.3
Cotton-wheat-vetch	6.4	2.6	3.9	12.9	5.2	4.4	2.8	5.1	12.3	4.9
SEM	0.23	0.09	0.35			0.27	0.23	0.38		
P <	0.001	ns	ns			0.01	ns	ns		

[1] Wheat dry matter was not directly measured during 2007 but was estimated from relationship between wheat grain yield and DM for this site.