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Sequestering carbon in minimum-tilled clay soils used for irrigated cotton and grain production

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ABSTRACT

Soil organic carbon (SOC) increased throughout a 10-year monitoring period (1998–2008) in an experiment that compared five cotton-based cropping systems. These systems included faba bean, vetch and wheat crops, as well as fallows of up to 10 months. All crops were grown on permanent ridges using minimum tillage. Topsoil (0–30 cm) contained between 40 and 42 t SOC ha^{-1} in 1998 and increased by 0.28 t C ha^{-1} yr^{-1} across the five cropping systems (range 0.18–0.45 t C ha^{-1} yr^{-1}, or 0.66–1.65 t CO_2e ha^{-1} yr^{-1}). In 2006 and 2008, SOC was measured to 90 cm depth; this indicated that on average 2.1 t C ha^{-1} yr^{-1} (range 1.1–3.8 t C ha^{-1} yr^{-1}) was sequestered (equivalent to 7.8 t CO_2e ha^{-1} yr^{-1}). The greatest accretions of C occurred in the subsoil: 14%, 67% and 19% of the sequestered-C was found in the 0–30, 30–60 and 60–90 cm depth intervals, respectively. SOC was 7% higher in the cropping systems that received legume stubble, which had higher N content. Faba bean and vetch stubbles averaged 2.89 and 3.89% N, whereas wheat and cotton stubbles averaged 0.78 and 1.56% N, respectively. Carbon inputs from crop stubble (excluding roots) ranged from 11.8 to 29.6 t C ha^{-1} over the 10-year period. Sequestered C exceeded the estimated CO_2e emissions typical of irrigated cotton cropping systems.

1. Introduction

Soil organic C (SOC) commonly declines in intensive cropping systems, especially with conventional tillage and poor stubble management (Wang and Dalal, 2006). Much of the SOC lost from arable soils can be attributed to cultivation, the return of N-depleted stubble, long fallows and the excessive use of N fertiliser (Khan et al., 2007). It is common for cotton producers to report low or declining SOC under current soil management practices of conventional tillage, high N fertiliser rates, long fallows and the return of N-depleted residues of only cotton (*Gossypium hirsutum* L.) and wheat (*Triticum aestivum* L.) crops. SOC is an important indicator of soil health, as it provides energy for microbial populations, conserves nutrients and helps maintain soil physical properties, including structure and water holding capacity and improves water infiltration.

The amount of C stored in the soil is often limited by the quantity of stubble returned (Koga and Tsuji, 2009). Crops that are irrigated and optimally fertilised may produce more biomass and therefore more stubble (Campbell et al., 2001; Follett et al., 2005). SOC can increase where minimum or reduced tillage is adopted and long fallows eliminated from the cropping system (Campbell et al., 2007; Bremner et al., 2008).

Soil C sequestration represents a significant sink for atmospheric CO_2 (Fornara and Tilman, 2008), although Lal (2007) suggests that globally, soils may only sequester about 15% of the C emitted from the burning of fossil fuels. Soils sequestering 1–2 t C ha^{-1} yr^{-1} are common reported (Campbell et al., 2000; Diekow et al., 2005; Follett et al., 2005; Barthes et al., 2006).

A cropping systems experiment that commenced in 1995 was chosen to assess SOC; measurements were taken every 2 years from 1998 to 2008. The experiment was initially designed to measure N fertiliser response and N fertiliser use-efficiency in irrigated cotton and grain crops. Substantial differences in yield and N fertility have been reported among the five cropping systems (Rochester et al., 2001; Rochester and Peoples, 2005).

The objectives of this study were to monitor changes in SOC under several cropping systems, to relate these changes to the quantity and quality of the stubble returned and to determine whether these changes were uniform through the soil profile and relate the levels of SOC observed to those in undisturbed soil under native vegetation.

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2. Materials and methods

2.1. Experiment site and soil description

The experiment was sited at Field 6 at the Australian Cotton Research Institute, Narrabri (149.6°E, 30.2°S), New South Wales, Australia. The soil is a fertile alkaline dark greyish brown cracking medium clay, classified as a fine, thermic, montmorillonitic Typic Haplustert (Soil Survey Staff, 1996). Soil surface pH was 7.9, EC 1.2 dS m^{-1}, CEC 35 meq 100 g^{-1}, and Colwell bicarbonate-P was 61 mg kg^{-1}. Despite there having been irrigated cotton and wheat cropping at this site for 25 years prior to this experiment, responses to fertilizers other than N have not been recorded in cotton. The climate is subtropical; soil temperatures (10 cm at 09.00 h) range from 10 to 29 °C. Annual rainfall averages 645 mm but is highly variable (420 and 870 mm for first and ninth deciles) and is slightly summer-dominant.

2.2. Experiment design

The experiment design and agronomic data relating to cotton N response and yields, including N_2 fixation in the legume crops, have been published (Rochester et al., 2001; Rochester and Peoples, 2005). The experiment was initiated in 1995, with five cropping treatments, replicated four times. These treatments included continuous cotton (cotton every summer) either with green-manured vetch (*Vicia villosa* Roth) each winter (CVCVC) or winter fallow (C∼C∼C), and three treatments that had cotton every second year, either with wheat then fallow (CW∼C), wheat then vetch (CWVC) or faba bean (*Vicia faba* L.) then fallow (CFb∼C). The ∼ symbol represents a fallow period of 5–10 months.

Cotton crops were fully irrigated and adequately fertilised with anhydrous ammonia, while all other crops were rain-grown. Wheat received 60 kg N ha^{-1} as urea before sowing. The legume seeds were inoculated immediately prior to sowing. Cotton, wheat and faba bean crops were harvested, while vetch was green-manured one month prior to sowing cotton.

Importantly, the experiment used a minimum tillage system where the 1 m spaced ridges (hills) were maintained throughout the experiment with shallow (10 cm depth) tillage to maintain the furrows between each crop, to control over-wintering pupae of *Helicoverpa* spp., and to incorporate herbicides and stubble. There was no deep cultivation.

2.3. Soil sampling and C analysis

SOC was measured in September in each even-numbered year, prior to applying N fertiliser and sowing the cotton crop that completed each rotation cycle. Soil was normally sampled 0–30 cm, but in 2004, 2006 and 2008, soil was also collected from 30 to 60 cm and in 2006 and 2008, from 60 to 90 cm, using a steel coring tube of 52 mm internal diameter. Two adjacent soil cores were collected from the top of the ridge and bulked for each sampling depth. Large tap roots of previous cotton crops were removed from the samples – all other particulate organic matter was included in the sample. Soil was dried at 50 °C and milled to a fine powder (<1 mm). SOC was determined by adding 10 ml 1 N potassium dichromate to 1 g soil, then 15 ml sulfuric acid. The suspension was diluted after cooling and centrifuged. Cr^{3+} produced from the oxidation of SOC was measured using a spectrophotometer at 600 nm. SOC is reported as t C ha^{-1} as determined from the SOC concentration and soil bulk density, which was estimated by weighing the dried soil from each 30 cm length of core, which had a volume of 637 cm^3. Soil bulk density was measured in 2006 and 2008 only; values for 2006 were used to report SOC as t C ha^{-1} for samples collected prior to 2006. Soil bulk density was not affected by the cropping treatments and averaged 1.24, 1.48 and 1.51 g cm^{-3} for the 0–30, 30–60 and 60–90 cm depth intervals, respectively.

In 2008, SOC was determined in an area of native vegetation (native grasses, forbs and scattered trees) about 400 m from the experiment site; the soil type was identical to the site of the experiment. Duplicate cores were combined to produce four replicate profiles from this area. Soil was sampled from areas between plants, using the same depth increments and analysed as for the experiment. Soil bulk density for this site was 1.27, 1.48 and 1.45 for the 0–30, 30–60 and 60–90 cm depth intervals, respectively.

2.4. Crop DM and stubble quality

Crop dry matter (DM) was measured at peak biomass by harvesting 1 m^2 from each replicate plot of cotton, vetch, faba bean or wheat. The vetch crops were green-manured by slashing and incorporating residues four weeks before sowing cotton. For all other crops, the dry residues that remained after picking or harvesting were slashed and incorporated into the topsoil (0–10 cm) with rolling cultivators or power harrows.

The quantities of stubble-C returned in each crop were estimated from the crop biomass-C minus the C removed in the grain or seed cotton. Stubble from all crops was assumed to contain 40% C.

Similarly, the N concentration of each crop stubble was estimated from the N content of the crop DM collected at peak biomass minus the N removed in grain (faba bean and wheat) or seed cotton, divided by the crop DM. Crop and seed N concentrations were measured by Kjeldahl analysis.

2.5. Statistical analyses

The Genstat program (Payne, 1987) was used for ANOVA. Linear regression analyses were performed using the SigmaPlot V9.0 program (Systat Software Inc., 2004). *, **, *** denote statistical significance i.e., $P < 0.05$, $P < 0.01$, $P < 0.001$, respectively; ns denotes not statistically significant.

3. Results

The concentrations (%) of SOC measured during the monitoring period are shown in Fig. 1a–c. The corresponding soil bulk density measurements are shown in Fig. 1d–f. The differences observed in soil bulk density between the cropping systems at each sampling time and depth were not statistically significant. The quantities of SOC (t C ha^{-1}) determined are shown in Fig. 2.

3.1. Quantities of organic C measured in topsoil

The SOC measured in the topsoil (0–30 cm) increased in all cropping systems over the 10-year monitoring period (Fig. 1a). In 1998, SOC averaged 39.4 t C ha^{-1} and in 2008, averaged 42.7 t C ha^{-1} (Fig. 2a). Linear regression for each cropping system indicated that SOC increased by 0.21, 0.35, 0.20, 0.45 and 0.18 t C ha^{-1} yr^{-1} for the C∼C∼C, CVCVC, CW∼C, CWVC and CFb∼C systems, respectively and by 0.28 t C ha^{-1} yr^{-1}, meaned across the five cropping systems. The two traditional and most dominant cropping systems used in Australia (CW∼C and C∼C∼C) maintained the lowest levels of SOC throughout the experiment, but still sequestered SOC.

3.2. Quantities of organic C measured in subsoil (30–90 cm)

SOC increased in the 30–60 cm level by 1.50 t C ha^{-1} yr^{-1} between 2006 and 2008 and by 0.43 t C ha^{-1} yr^{-1} in the 60–90 cm

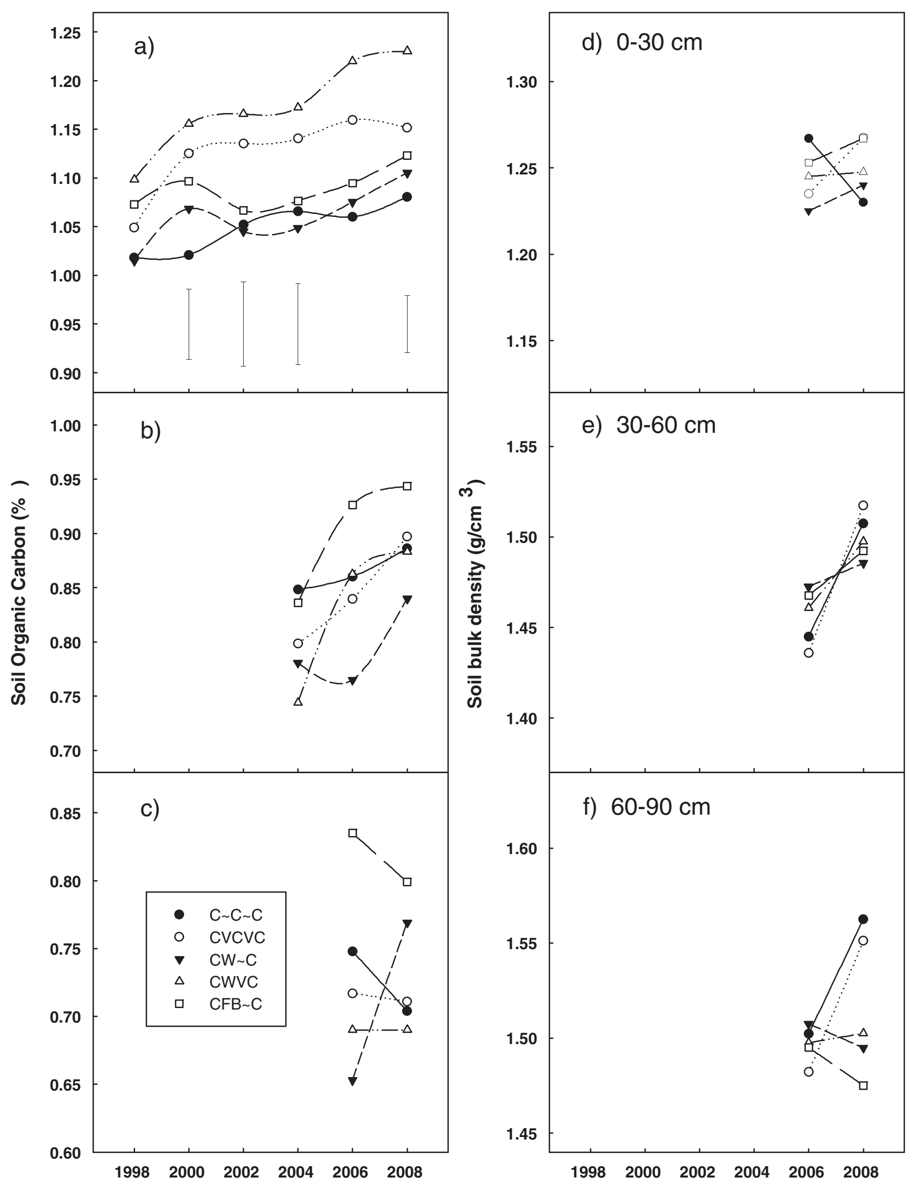

Fig. 1. Soil organic C (%) as measured at 0–30, 30–60 and 60–90 cm, and associated soil bulk density at the same depth intervals and sampling times within a cropping systems experiment. Bars represent the lsd ($P = 0.05$).

level between 2006 and 2008, averaged over the five cropping systems (Fig. 2b and c). SOC decreased with depth in the soil profile, but the changes in SOC were greater in the subsoil (30–60 cm) than in the topsoil (Figs. 1 and 2). There were no statistically significant differences between the cropping systems in the quantities of SOC sequestered in the subsoil.

Between 2006 and 2008, SOC increased in the topsoil by 0.31 t C ha^{-1}; thus, SOC increased by 4.4 t C ha^{-1} when averaged across all cropping systems to 90 cm depth. The 0–30, 30–60 and 60–90 cm depth intervals contributed 14, 67 and 19% of the total C sequestered during this period.

3.3. *Quantities of organic C measured under native vegetation in 2008*

Topsoil (0–30 cm) at the experiment site contained 28% less SOC than the native vegetation site (Table 1). However, at 30–60 cm depth, the experiment site contained 9% more SOC than the native vegetation site and at 60–90 cm, contained 6% (ns) more

Table 1
Changes in quantities of SOC at adjacent sites supporting native vegetation or an irrigated cropping experiment.

Soil depth (cm)	Native vegetation (t C ha^{-1})	cropping experiment (t C ha^{-1})	ΔSOC (%)
0–30	59.2 ± 1.8	42.7 ± 1.0	−28%***
30–60	37.2 ± 1.5	40.5 ± 0.5	+9%*
60–90	31.6 ± 1.5	33.5 ± 0.8	+6% ns

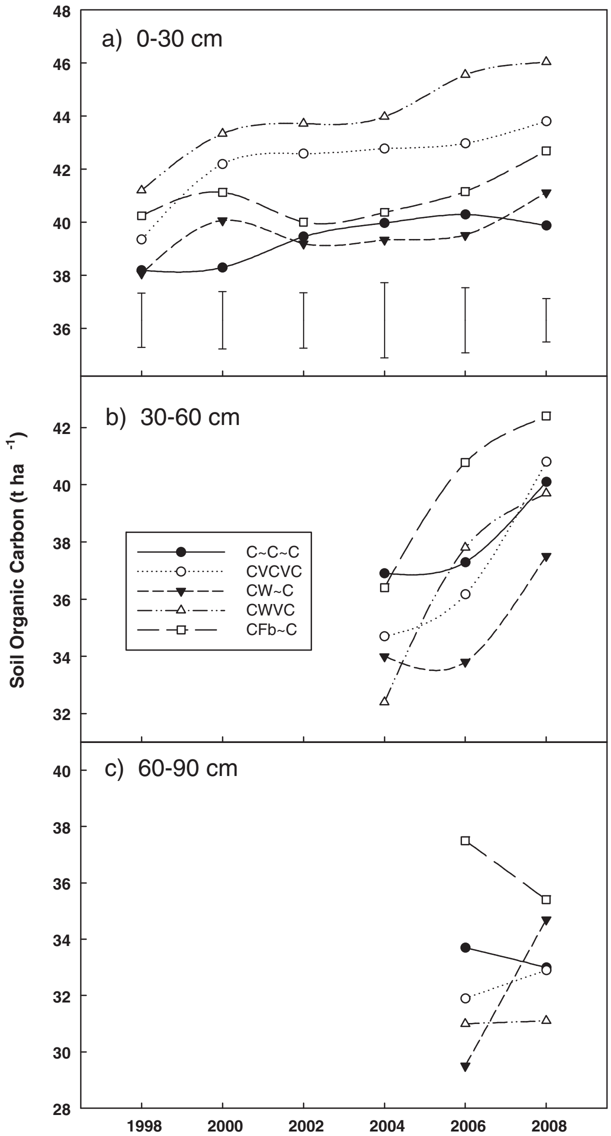

Fig. 2. Soil organic carbon measured over a 10-year period within a cropping systems experiment. Bars represent lsd ($P = 0.05$).

SOC than the native vegetation site. SOC declined with depth at both sites, but the distribution of SOC down the soil profile differed between the two sites.

3.4. Quantities of C added in crop stubble

The C added as crop stubble was summed over each 2-year rotation cycle from the start of the experiment (1995–2008) (Fig. 3). The highest cumulative amount of C (38 t C ha^{-1}) was

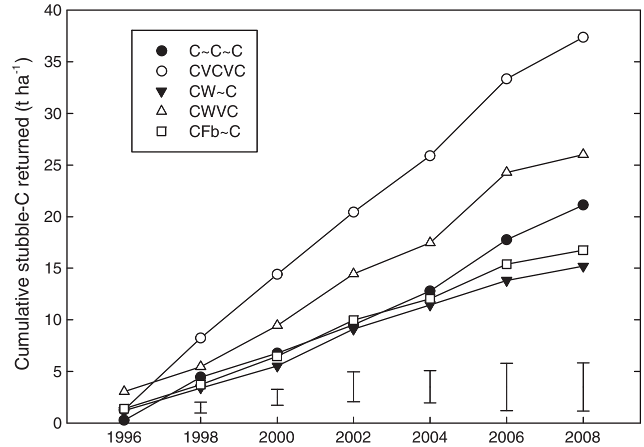

Fig. 3. Carbon returned in crop stubble during the experiment. Substantially more C was added to some treatments before the first SOC measurement in 1998. Stubble-C data do not include the C contained in or exuded from the roots of those crops. Bars represent lsd ($P < 0.05$).

added in the CVCVC system where crops were grown each winter and summer. Apart from CFb~C, the two non-legume systems (C~C~C and CW~C) had the lowest C inputs, which reflect the longer fallow times and fewer crops that provided stubble. Importantly, the amounts of stubble-C added between 1995 and 1998 differed among the five cropping systems (Fig. 3). This probably contributed to the differences in SOC measured among systems when first measured in 1998 (Figs. 1 and 2).

The total C input of the crop stubbles within each cropping system is shown in Table 2. On average, each cotton crop returned 1.66 t C ha^{-1}, faba beans 1.05 t C ha^{-1}, wheat 1.40 t C ha^{-1} and vetch 1.47 t C ha^{-1}. Between 1.2 and 3 t C ha^{-1} were returned to the soil in crop stubble each year.

The mean N concentrations of the wheat, cotton, faba bean and vetch stubbles averaged 0.78% (±0.06), 1.56% (±0.14), 2.89% (±0.36) and 3.89% (±0.11), respectively. The mean N concentration for all of the stubble added to each cropping system over the 10-year period were estimated as 1.56, 2.33, 1.20, 2.16 and 2.08% N for the C~C~C, CVCVC, CW~C, CWVC and CFb~C systems, respectively.

3.5. Relating quantity and quality of stubble input to SOC

The quantities of crop stubble-C, stubble-N returned and stubble C:N ratio were poorly correlated with SOC in the topsoil and soil profile (Fig. 4). However, there was a consistent separation of data in Fig. 4 that was related to the cropping systems that included legume crops (open symbols) and those that did not include legume crops (closed symbols). These differences were statistically significant ($P < 0.05$ – Table 3).

The systems that included legume crops returned 49% more stubble-C and 133% more stubble-N than the non-legume systems. Also, the C:N ratio of the stubble returned to the legume systems

Table 2
Cumulative stubble-C returned between 1998 and 2008.

Cropping system	Cotton (t C ha^{-1})	Wheat (t C ha^{-1})	Vetch (t C ha^{-1})	Faba bean (t C ha^{-1})	Total (t C ha^{-1})
C~C~C	16.7 b				16.7 c
CVCVC	19.8 a		9.8 a		29.6 a
CW~C	6.3 c	5.5 a			11.8 d
CWVC	7.0 c	6.7 a	7.7 b		21.4 b
CFb~C	7.5 c			4.7	12.2 d
lsd ($P < 0.05$)	1.9	ns	1.3		2.9

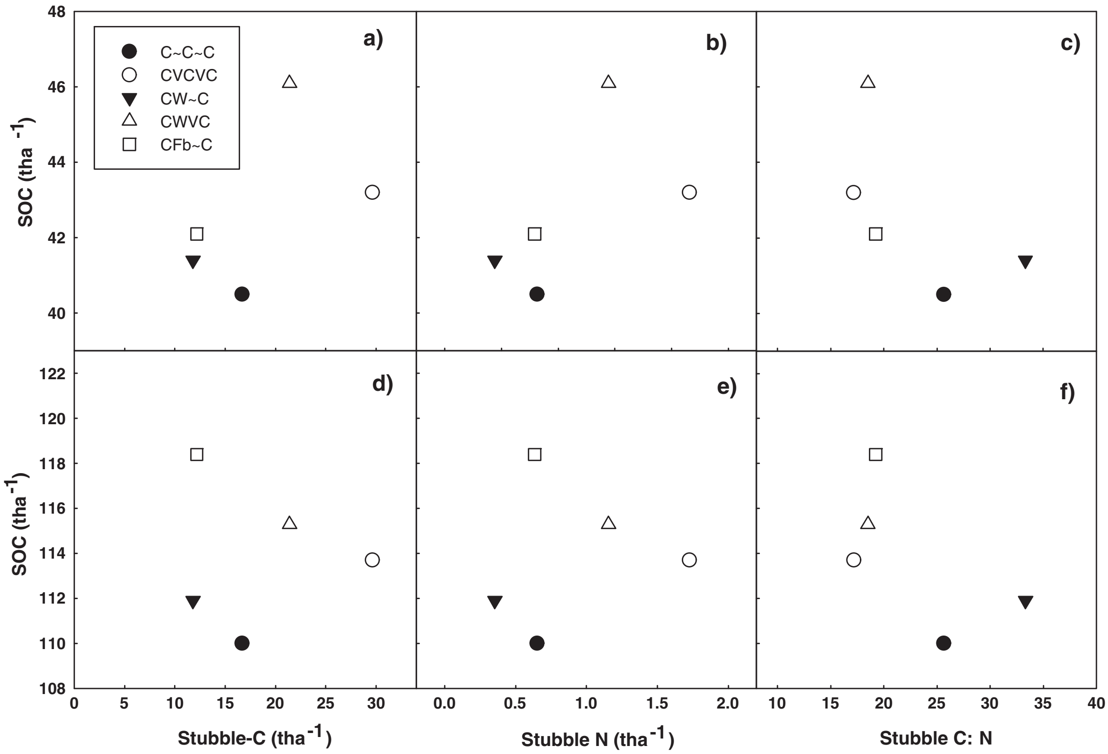

Fig. 4. Relationships between SOC and stubble-C returned in a) topsoil and d) profile to 90 cm, and SOC with stubble-N in b) topsoil and e) profile to 90 cm, and SOC with stubble C:N in c) topsoil and f) profile to 90 cm, within each cropping system.

was substantially lower. Accordingly, the SOC in the legume systems was 6.8% higher in the topsoil (0–30 cm) and 6.7% higher in the subsoil at the end of the experiment.

A further effect of including legumes was observed when the CW∼C and CFb∼C systems were compared. Over the 10-year period, the five faba bean crops added 4.7 t C ha^{-1} (Table 2), whereas the five wheat crops added 5.5 t C ha^{-1} (i.e., 16% more stubble-C). Despite this, SOC was 0.7 t C ha^{-1} (1.6%) lower in the topsoil of the CW∼C system compared with CFb∼C and 6.5 t C ha^{-1} (8.6%) lower over the profile to 90 cm when measured in 2008 (Fig. 4a and d).

4. Discussion

4.1. Soil C sequestration

SOC increased consistently in the topsoil of all cropping systems. The systems that returned greater quantities of stubble-C or produced stubble of higher N concentration (i.e., legume stubble – Table 3) showed greater or more rapid increases in SOC (Figs. 1 and 2). However, Hulugalle (2000) found SOC (measured to 60 cm depth) declined over a 5-year period in a field close to the cropping systems experiment used in this study, even in treatments under minimum tillage.

There were greater increases in SOC in the subsoil, compared with the topsoil. Increases in subsoil SOC may result from soluble SOC moving through the soil profile, particularly during flood irrigation, as well as from stubble falling and being washed into the cracks that form in swelling, self-mulching soil. This may also explain higher SOC in the subsoil in the site of the experiment compared with the native vegetation site that was not irrigated (Table 1). The data also suggest SOC may move beyond 90 cm depth in this soil type. In contrast, D'Haene et al. (2009) observed that SOC accumulated near the surface rather than at depth in silt loam soils under reduced tillage in Western Europe. SOC can be maintained in the surface (30 cm) soil under irrigated maize and soybean monocultures (Varvel and Wilhelm, 2008) but they did not investigate SOC changes in the subsoil. SOC in soil under native vegetation near the site of the experiment was higher in the topsoil but slightly lower in the subsoil compared with the experiment site (Table 1). As the data indicate that C was sequestered into the subsoil, past management practices depleted subsoil SOC levels, which may recover as C conservation practices (e.g., minimum tillage, stubble incorporation) are employed.

Grace (2008) produced a model to estimate CO_2e emissions from cotton fields, based on fuel and energy use, the area under cotton production and N fertiliser use. Estimated C emissions were 1.2 t CO_2e ha^{-1} yr^{-1} (or 0.33 t C ha^{-1} yr^{-1}) from a typical Australian irrigated cotton field. This figure is close to the C sequestered in the topsoil of the experiment presented here. This indicates that the large amounts of C sequestered in the subsoil were excess to the CO_2e emitted through cotton production and indicates the importance of

Table 3
Quantities of stubble-C and stubble-N returned and stubble C:N ratio over the previous 10 years and the SOC in the topsoil (0–30 cm) and soil profile (0–90 cm) at the end of the monitoring period. Means followed by a different letter were statistically different ($P < 0.05$).

Cropping systems	Stubble-C (t ha^{-1})	Stubble-N (t ha^{-1})	Stubble C:N	SOC 0–30 cm (t ha^{-1})	SOC 0–90 cm (t ha^{-1})
Legume	21.1 a	1.171 a	18.3 a	43.8 a	116.5 a
Non-legume	14.2 b	0.502 b	29.5 b	41.0 b	109.2 b

including subsoil C sequestration in C balance, particularly in irrigated systems. This is neglected in most C sequestration studies.

4.2. Stubble-C return

The amounts of stubble-C returned do not include roots and root exudates, which can represent a substantial input of SOC (Fig. 3; Tables 2 and 3). Constable et al. (1992) and Hodgson et al. (1990) estimated that cotton crops grown near the site of the current cropping systems experiment contributed 0.8–1.1 t C ha^{-1} respectively from their root systems; this would be equivalent to an additional 50–70% of the 1.56 t C ha^{-1} returned per cotton crop in stubble within the experiment. Similar amounts would be returned in the roots of the wheat, vetch and faba bean crops. Sun et al. (2009) estimated that an average of 5.78 t C ha^{-1} was sequestered in croplands of Eastern China between 1980 and 2000 as a result of increased biomass production and stubble retention.

Long fallows were avoided in the CVCVC and CWVC cropping systems where crops were grown almost continually; this produced more stubble and returned more C to the soil (Fig. 3), compared with the C∼C∼C, CW∼C and CFb∼C systems where soil was fallowed for several months in each 2-year cycle. Hence, the CVCVC and CWVC systems contained the highest SOC in the topsoil (Figs. 1 and 2).

4.3. Stubble quality (N content) and legume cropping

Stubble quality is all-important in increasing SOC (Gregorich et al., 2001). Legume stubbles have higher N content than cereal or cotton stubble that will be more similar to the C:N ratio of the soil biota (Suman et al., 2006). Further, Suman et al. (2006) observed that the soil microbial biomass C:N was influenced by the quality of the stubble added; legume stubble resulted in microbial C:N of ∼11.3, whereas non-legume stubble produced soil microbial biomass C:N of ∼17.3. In the non-legume systems used in the experiment, the quality of the wheat and cotton stubbles returned were of low N content (0.78% and 1.56% N, respectively), while legume stubbles averaged 3.39% N (Table 3). This equates to stubble C:N ratios of 51.3, 25.6, 13.8 and 10.3 for wheat, cotton, faba bean and vetch, respectively.

The experiment demonstrated that including legume crops into cotton cropping systems can result in greater sequestration of SOC (Table 3). Growing legume rotation crops benefits greenhouse gas abatement in two ways. Firstly, the loss of the stubble-C from the soil is decreased where the stubble C:N ratio is narrow (Suman et al., 2006) so that stubble-C is more completely incorporated into the soil microbial biomass and secondly, N_2O emissions are small where legumes and little or no fertiliser-N are used (Rochette and Janzen, 2005). Curtin et al. (2000) and Campbell et al. (2007) suggested that legume crops promoted the conversion of stubble-C to soil SOC, as was evident in the experiment.

Mortenson et al. (2004) found SOC increased by up to 17% over 33 years where *Medicago sativa* was sown into native pasture. Legume cropping may increase SOC as well as improve soil quality and the system's productivity (Wani et al., 2003). Diekow et al. (2005), Barthes et al. (2006) and Campbell et al. (2007) all reported that legume cropping elevated the rates of C sequestration. Legumes may dramatically increase SOC accumulation, especially in combination with C4 grasses (Fornara and Tilman, 2008). Rusinamhodzi et al. (2009) demonstrated that the addition of narrow and wide C:N crop stubbles can enhance C sequestration, as well as C and N cycling in the soil and N-use efficiency. This was confirmed in the experiment where legume and cotton crop residues were added, albeit at different times, increased the rate of C sequestration.

4.4. Stubble management

Stubble incorporation is important to retain soil C and N; all stubble was incorporated into the topsoil in the experiment. Asagi and Ueno (2009) reported that N losses were reduced where green-manured legume crops (vetch and clover) were incorporated, compared with leaving the stubble on the surface. Also, Novak et al. (2009) showed a significant decline in topsoil SOC under conservation tillage where stubble was not incorporated.

4.5. Tillage

The experiment data relate to cotton cropping systems that are based on minimum-tillage whereby the ridges and furrows are maintained permanently. White and Rice (2009) indicate that reduced tillage promotes higher C sequestration. Roldan et al. (2005) and White and Rice (2009) observed increased levels of soluble C, enzyme activity, aggregate stability and glomalin in no-tilled soil compared with tilled soil. However, Poirier et al. (2009) noticed differences in SOC in the surface soil between no-till and moldboard plowing treatments but no differences when the soil profile was considered. SOC declines more quickly under intensive tillage than minimum tillage (Hulugalle, 2000). Increases in SOC may be short-lived where the system is changed to include longer fallows or deep cultivation (Dersch and Bohm, 2001; Bremner et al., 2008; D'Haene et al., 2009).

4.6. Irrigation

Irrigation enhances crop biomass production (Gillabel et al., 2007) and thereby increases the amounts of stubble-C returned to the soil (Follett et al., 2005; Denef et al., 2008). Over a 50-year period, both SOC and SIC (soil inorganic carbon) increased in two irrigated Californian soils, relative to adjacent native soils (Wu et al., 2008). Gillabel et al. (2007) described increased SOC with irrigation, as SOC was protected from decomposition within soil micro-aggregates.

The data from the experiment suggest that the high levels SOC in the subsoil may be related to infiltration of irrigation water. Carbon can be sequestered in and below the crop root zone from dissolved organic carbon that has moved through the soil profile (Artiola and Walworth, 2009). This is supported by data from the experiment, where most of the SOC sequestered between 2006 and 2008 appeared in the subsoil. Diekow et al. (2005) indicated that much of the C lost from or sequestered to the soil was from below the surface 17.5 cm and that 42% of the C sequestered was found below this depth.

5. Conclusions

This study has shown that substantial amounts of C can be sequestered in irrigated cotton-growing soils where stubble is incorporated under a minimum tillage regime. Higher rates of C sequestration were observed in those systems that included legume crops. Greater C sequestration occurred in the subsoil, than in the surface soil (0–30 cm). To sequester C in soils, it is imperative that management practices include reduced (minimum) tillage, avoiding long fallows and conserving stubble, while optimizing fertiliser inputs and water management. This research has demonstrated that it is possible to balance C emissions from high-yielding irrigated cotton production by sequestering atmospheric CO_2 into SOC.

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