

Sequestering Carbon in Irrigated Cotton Soils

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Summary

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 in 1998 and increased by 0.28 t C/ha/yr (or 0.51 to 1.69 t CO₂e/ha/yr) across the five cropping systems. Between 2006 and 2008, SOC was measured to 90 cm depth; this indicated that on average 2.2 t C/ha/yr was sequestered (equivalent to 8.1 t CO₂e/ha/yr). The greatest accretions of C occurred in the subsoil: 13%, 38% and 49% 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. 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 (C) inputs from crop stubble (excluding roots) ranged from 11.8 to 29.6 t C/ha over the 10-year period. Sequestered C vastly exceeded the estimated CO₂e emissions typical of irrigated cotton cropping systems.

Keywords: carbon sequestration; soil organic carbon; cotton stubble; legume stubble; minimum tillage

Materials and Methods

Experiment site

The experiment was sited at Field 6 at the Australian Cotton Research Institute, Narrabri New South Wales. The soil is a fertile, alkaline, dark greyish-brown, cracking, medium clay. The experiment includes 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 to 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 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.

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 ended each rotation cycle. Soil was normally sampled 0-30 cm, but in 2004, 2006 and 2008, soil was also collected from 30-60 cm and in 2006 and 2008, from 60-90 cm using a steel coring tube of 52 mm internal diameter. Soil was dried at 50°C and milled to a fine powder (<1 mm). SOC was determined using dichromate oxidation. SOC is reported as t C /ha as determined from the SOC concentration and soil bulk density. Soil bulk density was not affected by the cropping treatments and averaged 1.25, 1.44 and 1.48 g/cm at 0-30, 30-60 and 60-90 cm depth, 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.

Results

Quantities of SOC measured in topsoil

The SOC measured in the topsoil (0-30 cm) increased in all cropping systems over the 10-year monitoring period (Fig. 1). In 1998, SOC averaged 39.4 t C/ha and in 2008, averaged 42.7 t C/ha. Linear regression for each cropping system indicated that SOC increased by 0.24, 0.33, 0.25, 0.46 and 0.14 t C/ha/yr for the C~C~C, CVCVC, CW~C, CWVC and CFb~C systems, respectively and by 0.28 t C/ha/yr, 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.

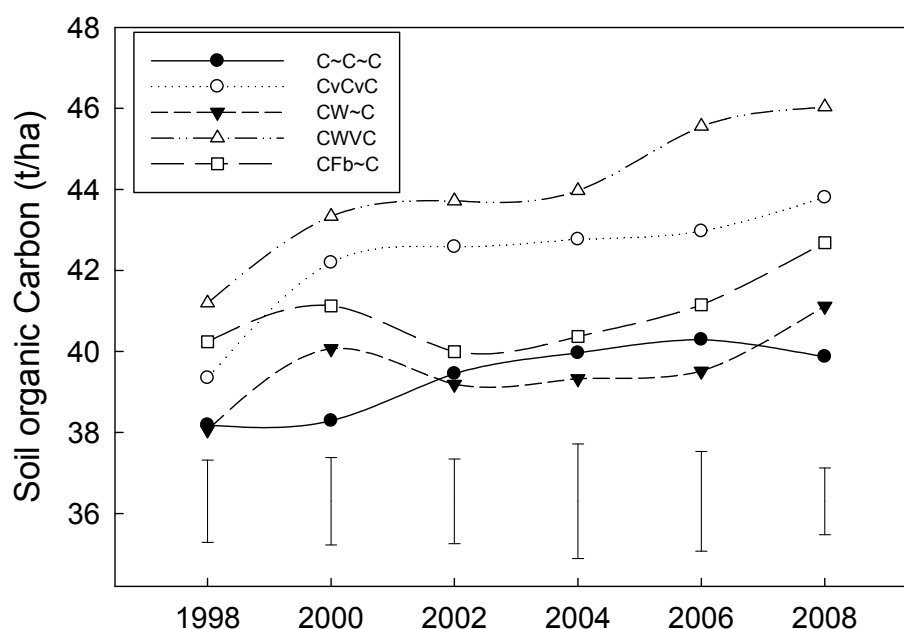


Fig. 1. Soil organic carbon measured in the topsoil (0-30 cm) over a 10-year period within the cropping systems experiment.

Quantities of SOC measured in subsoil (30 - 90 cm)

SOC increased in the 30-60 cm level by 1.4 t C/ha/yr between 2006 and 2008 and by 2.4 t C/ha/yr in the 60-90 cm level between 2006 and 2008, averaged over the cropping systems (Fig. 2). SOC decreased with depth in the soil profile, but the changes in SOC were greater in the subsoil than in the topsoil (Figs. 1 and 2). The CFb~C, CW~C and CWVC systems showed the greatest change in subsoil SOC levels. Between 2006 and 2008, SOC increased in all cropping systems to 90 cm depth by an average of 4.4 t C/ha.

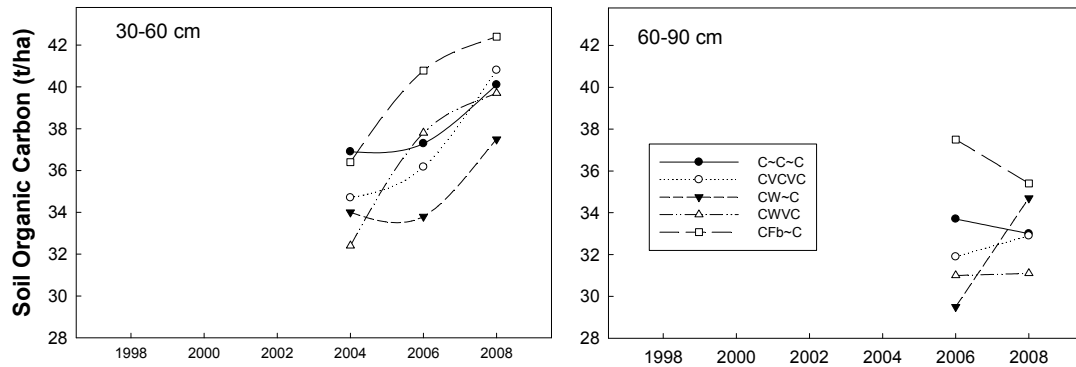


Fig. 2. Soil organic carbon measured in the subsoil of the cropping systems experiment.

Quantities of SOC measured under native vegetation in 2008

Topsoil (0-30 cm) at the experiment site contained 28% less SOC than the native vegetation site (Fig. 3). However, at 30-60 cm depth, the experiment site contained 3% more SOC than the native vegetation site and at 60-90 cm, contained 10% more 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.

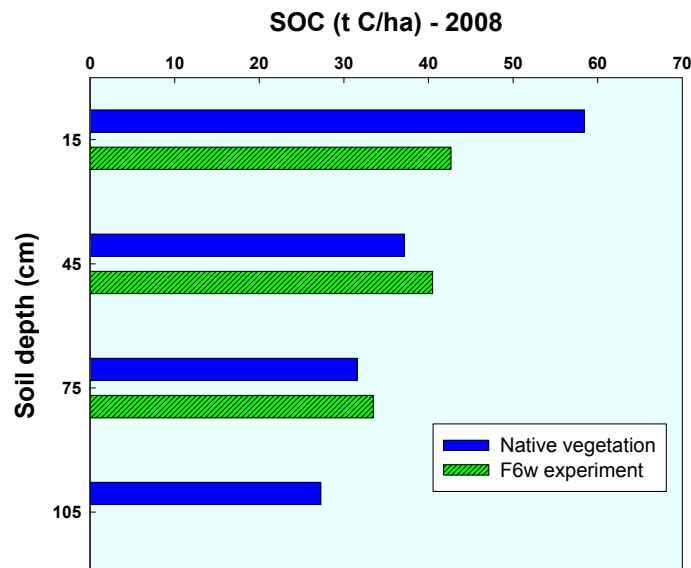


Fig. 3. Soil organic carbon measured in the soil profiles of the cropping systems experiment and an adjacent undisturbed native vegetation site.

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) to 2008. The highest cumulative amount of C (38 t C/ha) was 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.

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 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, whereas the five wheat crops added 5.5 t C/ha (i.e. 16% more stubble-C). Despite this, SOC was 0.7 t C/ha (1.6%) lower in the topsoil of the CW~C system compared with CFb~C and 6.5 t C/ha (8.6%) lower over the profile to 90 cm when measured in 2008.

Discussion

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) showed greater or more rapid increases in SOC (Fig. 1). However, Hulugalle (2000) found SOC (measured to 60 cm depth) declined over a 5-year period in a field close to the experiment, 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 (Fig. 3). The data also suggest SOC may move beyond 90 cm depth in this soil type. The native vegetation site had more SOC in the topsoil but slightly lower in the subsoil compared with the experiment site (Fig. 3). 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 C 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 CO₂e/ha/yr (or 0.33 t C/ha/yr) 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 CO₂e emitted through cotton production and indicates the importance of including subsoil C sequestration in C balance, particularly in irrigated systems. This is neglected in most C sequestration studies.

Stubble-C return

The amounts of stubble-C returned do not include roots and root exudates, which can represent a substantial input of SOC. However, cotton crops grown near the site of the F6 experiment have contributed 0.8 to 1.1 t C/ha respectively from their root systems; this would be equivalent to an additional 50-70% of the 1.56 t C/ha 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.

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, 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 (Fig. 1).

Stubble quality (N content) and legume cropping

Stubble quality is all-important in increasing SOC. 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. The soil microbial biomass C:N is 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. 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 (Fig. 1). 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 so that stubble-C is more completely incorporated into the soil microbial biomass and secondly, N₂O emissions are small where legumes and little or no fertiliser-N are used (Rochette and Janzen, 2005). Campbell et al. (2007) suggested that legume crops promoted the conversion of stubble-C to soil SOC, as was evident in the experiment. Legume cropping may increase SOC as well as improve soil quality and the system's productivity. Many researchers have reported that legume cropping elevated the rates of C sequestration.

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.

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 who also observed increased levels of soluble C, enzyme activity, aggregate stability and glomalin in no-tilled soil compared with tilled soil. 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.

Irrigation

Irrigation enhances crop biomass production and thereby increases the amounts of stubble-C returned to the soil. 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. 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.

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 CO₂ into SOC.

Acknowledgements

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