CSIRO PUBLISHING
Crop & Pasture Science, 2013, **64**, 845–855
http://dx.doi.org/10.1071/CP13139

Maximum ambient temperature can influence carbon storage in Vertosols sown with cotton-based farming systems

N. R. Hulugalle

NSW Department of Primary Industries, Australian Cotton Research Institute, Locked Bag 1000, Narrabri, NSW 2390, Australia. Email: nilantha.hulugalle@dpi.nsw.gov.au

Abstract. Partial mitigation of global warming caused by accelerated emissions of greenhouse gases such as carbon dioxide may be possible by storing atmospheric carbon in soils. Carbon storage is influenced by processes and properties that affect soil aggregation, such as clay and silt concentrations and mineralogy, intensity and frequency of wet/dry cycles, and microbial activity. Microbial activity, in turn, is influenced by factors such as temperature, nutrient and water availability, and residue quality. The objective of this study was to assess the influence of average annual maximum temperature on soil carbon storage in Vertosols under cotton-based farming systems. This paper reports a re-evaluation of results obtained from a series of experiments on cotton-farming systems conducted in eastern Australia between 1993 and 2010. The experimental sites were in the Macquarie and Namoi Valleys of New South Wales, and the Darling Downs and Central Highlands of Queensland.

Average soil organic carbon storage in the 0–0.6 m depth was highest in a Black Vertosol in Central Queensland and lowest in a Grey Vertosol that was irrigated with treated sewage effluent at Narrabri. At other sites, average values were generally comparable and ranged from 65 to 85 t C/ha. Climatic parameters such as ambient maximum temperature, T_{max}, and rainfall at rainfed sites (but not irrigated sites) were also related to soil organic carbon storage. At most sites, variations in carbon storage with average ambient maximum temperature were described by Gaussian models or bell-shaped curves, which are characteristic of microbial decomposition. Carbon storage occurred at peak rates only for a very limited temperature range at any one site, with these temperatures increasing with decreasing distance from the equator. The exception was a site near Narrabri that was irrigated with treated sewage effluent, where the relationship between soil organic carbon and T_{max} was linear. The decrease or absence of change in soil carbon storage with time reported in many Australian studies of annual cropping systems may be due to carbon storage occurring within a limited temperature range, whereas intra-seasonal average maximum temperatures can range widely. Further research needs to be conducted under field conditions to confirm these observations.

Additional keywords: farming system, Haplustert, irrigation, residue management, rotation, temperature, tillage, Vertisol.

Received 31 December 2012, accepted 2 October 2013, published online 29 October 2013

Introduction

Partial mitigation of global warming caused by accelerated emissions of greenhouse gases such as carbon dioxide may be possible by storing atmospheric carbon in soils (Lal 2009; Lal and Follett 2009; Stockmann 2011). Most field research programs associated with agriculture have attempted to do this primarily by enhancing biomass inputs through modifying tillage and residue management practices, adding organic waste products to soil, and changing cropping sequences (Lal 1997; Powlson *et al.* 2011; Stockmann 2011), rather than stimulating the processes associated with physical and biochemical protection of soil organic matter (Six *et al.* 2002). Although the previously mentioned practices could improve protection of soil organic matter as well, this has not been the primary objective of most studies (Lal 1997; Powlson *et al.* 2011; Stockmann 2011).

Carbon storage (physical and biochemical protection of soil organic matter) and post-storage losses are influenced by clay and silt concentrations and mineralogy, intensity and frequency of wet/dry cycles, and microbial activity (Six *et al.* 2000*a*, 2000*b*, 2002). Microbial activity, in turn, is influenced by factors such as temperature, nutrient and water availability, and residue amounts and quality (Russell 1973). These factors interact strongly, as the last two are strongly dependent on plant growth, which in turn is influenced by the first three factors. Among these factors, and despite several decades of research, the influence of temperature on losses and gains of soil carbon stocks is still subject to debate (Kirschbaum 2006). Most models (Cox *et al.* 2000; Stockmann 2011) suggest that increasing temperatures will result in declines in soil carbon stock, although Thornley and Cannell (2001) note that this may be a short-term response. Review of the literature of the past 20 years showed that of a total of 24 papers that had studied temperature–soil carbon interactions, 18 (75%) suggested that increasing air temperature was a major driving force of decomposition and SOM losses, whereas two (8%) reported that temperature had only a minor effect (Table 1). The latter group suggested that factors such as site management, nutrient

Table 1. Ambient temperature effects on soil organic carbon and its fractions, 1990–2011

Finding	Citation
Temperature was either explicitly or implicitly suggested as the major driver of SOM losses and CO_2 emissions from soil	Alvarez and Alvarez 2001; Arevalo *et al*. 2012; Balser and Wixon 2009; Cox *et al*. 2000; Craine *et al*. 2010; Dalal and Carter 2000; Davidson and Janssens 2006; French *et al*. 2009; Parkin and Kaspar 2003; Potter *et al*. 2007; Thornley and Cannell 2001; Townsend *et al*. 1992; Trumbore *et al*. 1996; Zhu and Cheng 2011; Kirschbaum 1995, 2006; Stockmann 2011; Waldrop and Firestone 2004; Vanhala *et al*. 2007
Temperature increases had only a small role in SOM losses, and was less influential than factors such as management, nutrient status, water availability, and clay content	Causarano *et al*. 2008; Garten *et al*. 2009
Temperature interacted with factors such as clay content, soil chemistry, nutrient status, and water availability	Craine and Gelderman 2011; Cox *et al*. 2000; Dalal and Carter 2000; Davidson and Janssens 2006; Lavoie *et al*. 2011; Parkin and Kaspar 2003; Potter *et al*. 2007; Yuste *et al*. 2007; Kirschbaum 2006; Stockmann 2011; Waldrop and Firestone 2004
Temperature-related increases in decomposition varied among individual SOM fractions	Arevalo *et al*. 2012; Lavoie *et al*. 2011; Thornley and Cannell 2001; Vanhala *et al*. 2007; Stockmann 2011; Waldrop and Firestone 2004
Microbial communities were associated with decomposition, and temperature response curves differed among climatic zones, but were independent of SOM quality	Balser and Wixon 2009
Decomposition and temperature response curves differed between SOM derived from plants of different photosynthetic pathways	Waldrop and Firestone 2004; Vanhala *et al*. 2007

status, water availability, and clay content affected carbon losses more than temperature did. Many publications (54%) also noted that a strong interaction existed between temperature and soil characteristics such as clay content, soil chemistry, nutrient status, and water availability, although despite the documented relationships between soil structure, temperature, and microbial activity (Torbert and Wood 1992; Watts *et al.* 2005; Schjønning *et al*. 2011), the interaction between soil structure and temperature on soil carbon stocks was not studied by any of the authors cited in Table 1.

The literature also suggests that temperature effects on the decomposition of different soil carbon fractions are variable (Table 1). Younger, labile soil organic carbon (SOC) is reported to be less sensitive to decomposition than older, more recalcitrant carbon as temperature increases (Waldrop and Firestone 2004; Vanhala *et al.* 2007; Arevalo *et al.* 2012). As the 'old' carbon in the study by Vanhala *et al*. (2007) was derived from a C_3 crop ('grains') and the 'new' carbon from a C_4 crop (maize, *Zea mays*), it is debatable whether the results are purely due to increasing temperature or whether there was an interaction between temperature and soil carbon derived from plants of differing photosynthetic pathways. A similar comment can be made with respect to the results of Waldrop and Firestone (2004), who compared 'old' soil carbon from tropical C_3 plants (mixed forest of *Hibiscus tiliaceus*, *Nephrolepis*, and *Gleichenia linearis*, *Psidium guajava*, *Pistache*, and *Eugenia cumini*) with 'new' carbon from pineapple (*Ananas comosus* var. *Quentii*), a CAM (crassulacean acid metabolism) plant. In contrast, a broader study that evaluated results from a range of climatic zones suggested that increasing temperatures may result in an increasing rate of conversion of unprotected (labile) carbon to more protected and stable carbon pools (Thornley and Cannell 2001). Other research in organic soils of tundra and boreal regions reports that addition of nitrogen stimulates decomposition of labile carbon, but suppresses that of recalcitrant carbon (Lavoie *et al*. 2011). Waldrop and Firestone (2004) suggest that such variable responses to changing temperature may be related to changes in soil microbial populations (i.e. decomposers). This is not surprising, as rapid and short-term changes and successions in microbial populations that were associated with short-term changes in soil physical properties have been reported by Hadas *et al*. (1994) and Rawitz *et al*. (1994). It may be surmised, therefore, that as fluctuations occur in temperature, and presumably other environmental variables such as water and nutrient availability, parallel changes in microbial populations that preferentially subsist upon different soil organic matter (SOM) fractions may also take place.

In summary, SOM changes in many soil types and climatic zones appear to be strongly influenced by ambient temperature, with interactions occurring with water and nutrient availability. Furthermore, given that the temperature–SOM relationship is a biologically driven process, it is far more likely that it is curvilinear rather than linear (Potter *et al.* 2007). Much of the research has, however, been conducted in non-swelling soils where storage of carbon occurs primarily through aggregation that involves a microbial component. No research has been conducted on SOC storage in Australian Vertosols and its relationship to ambient temperatures.

As cotton farming in Australia is conducted in tropical and subtropical climatic zones (Bange *et al.* 2010), it is unlikely that minimum temperatures (Table 2) in these zones will inhibit microbial activity for extended periods. Instead, it is far more likely that temperature-related activities will be controlled primarily by maximum temperatures, as midsummer values in cotton-farming regions frequently exceed 35°C, and values in >40°C are not uncommon (BOM 2011). Soil surface (0–0.10 m) temperatures that were similar or higher have been reported by several authors (Ross *et al.* 1985; Horton and Corkrey 2011; Horton 2012). The objective of this study, therefore, was to assess the influence of average annual maximum temperature

(January–December) on soil carbon storage in Vertosols sown with cotton-based farming systems. It was hypothesised that as soil carbon storage was a microbiologically driven process, the relationship between average maximum temperature and soil carbon storage would be best described by Gaussian or bell-shaped curves (Gendugov *et al.* 2011). This paper reports a re-evaluation of results obtained from a series of experiments on cotton-farming systems conducted in eastern Australia between 1993 and 2010. Previous research at these sites (Table 2) had shown that, in most, SOC stocks decreased with time, even though practices that are claimed to improve carbon had been in place for extended periods.

Material and methods

Experimental sites

Soil was sampled from several irrigated and dryland experimental sites in New South Wales and Queensland between 1993 and 2010 (Table 2). The cropping systems on these sites included continuous cotton (*Gossypium hirsutum* L.), cotton–rotation crop sequences, and 2-m ('broad beds') and 1-m ('ridges') beds. Minimum tillage or reduced tillage was practised in all sites. All mechanised traffic was restricted to the furrows. Locations of the sites, references in the literature, years and management practices investigated in each experiment, and soil types are reported in Table 2. The soils at all sites were classified as Vertosols (Isbell 2002) or Vertisols (Soil Survey Staff 2010). Some initial soil properties at these sites are summarised in Table 3. The specific cropping systems and land preparation for each site (Table 2) are summarised as follows.

Site 1: irrigated field (C1) at the Australian Cotton Research Institute (ACRI), Narrabri, NSW

The experiment consisted of: (*i*) continuous cotton (summer cotton–winter fallow–summer cotton) sown either after conventional tillage (slashing of cotton plants after harvest, followed by disc-ploughing and incorporation of cotton stalks to 0.2 m, chisel ploughing to 0.3 m, followed by 1-m bed construction) or on 1-m permanent beds (slashing of cotton plants after harvest, followed by root cutting, incorporation of cotton stalks into beds, and bed renovation with a disc-hiller); and (*ii*) a cotton–wheat (*Triticum aestivum* L.) rotation (summer cotton–winter wheat–summer and winter fallow–summer cotton) on permanent beds. Until 1999, wheat stubble was incorporated before sowing cotton, whereas from December

Table 2. Years and experimental sites from which soil was sampled

All Narrabri sites, Warren, and Merah North were irrigated; Warra and Emerald were not irrigated. Narrabri site 3 was irrigated with treated sewage effluent. T_{max} and T_{min}: Average annual maximum and minimum temperatures (± standard deviation), respectively, during the period of study. Values in parentheses for sites 1, 2, 3 and 5 are the averages (± standard deviation) from January 1911 to December 2011 for the town of Wee Waa, which lies within a radius of 15 km of these sites

Site	Location	Reference	Years	T_{max} (°C)	T_{min} (°C)	Management practices	Soil type
1	Narrabri (ACRI, Field C1), NSW (30°11′S, 149°36′E)	Hulugalle and Entwistle 1997; Hulugalle *et al.* 1997, 2005, 2010	1993–2009	26.9 ± 6.7 (26.8 ± 6.1)	12.1 ± 6.7 (11.6 ± 5.8)	Crop rotations, tillage systems, stubble management	Grey, self-mulching Vertosol; very fine
2	Narrabri (ACRI, Field D1), NSW (30°11′S, 149°36′E)	Hulugalle *et al.* 2012*a*, 2012*b*, 2013	2002–2010	27.0 ± 6.8 (26.8 ± 6.1)	12.2 ± 6.9 (11.6 ± 5.8)	Crop rotations, stubble management	Grey, self-mulching Vertosol; very fine
3	Narrabri, NSW (30°13′S, 149°43′E)	Hulugalle *et al.* 2006*a*	2000–2010	27.0 ± 6.8 (26.8 ± 6.1)	12.1 ± 6.9 (11.6 ± 5.8)	Stubble management, gypsum application	Grey, self-mulching Vertosol; medium fine
4	Warren, NSW (31°47′S, 147°46′E)	Hulugalle *et al.* 1998, 1999, 2006*b*	1993–2009	25.5 ± 7.4 (25.5 ± 6.6)	11.6 ± 6.7 (11.0 ± 5.7)	Crop rotations	Grey, self-mulching Vertosol; medium fine
5	Merah North, NSW (30°11′S, 149°18′E)	Hulugalle *et al.* 2002*a*, 2006*b*	1993–2005	27.0 ± 6.7 (26.8 ± 6.1)	12.0 ± 6.7 (11.6 ± 5.8)	Crop rotations	Grey, self-mulching Vertosol; very fine
6	Warra, Qld (26°56′S, 150°50′E)	Hulugalle *et al.* 2007	1996–2005	27.3 ± 4.7 (26.7 ± 4.9)	12.4 ± 5.5 (12.0 ± 5.5)	Crop rotations	Grey, self-mulching Vertosol; medium fine
7	Emerald, Qld (23°30′S, 148°08′E)	Hulugalle *et al.* 2002*b*	1996–2002	29.9 ± 4.2 (29.6 ± 4.5)	16.4 ± 4.9 (15.4 ± 5.2)	Crop rotations, bed widths, stubble management	Black, self-mulching Vertosol; very fine

Table 3. Some soil properties in the surface 0.3 m at the experimental sites

ESP, Exchangeable sodium percentage; $EC_{1:5}$, electrical conductivity of a 1 : 5 soil : water suspension; ESP, exchangeable sodium percentage; ESI, electrochemical stability index ($EC_{1:5}$/ESP); clay activity = cation exchange capacity (CEC)/clay content

Experimental site	Year	Clay (g/kg)	Sand (g/kg)	pH (0.01 M $CaCl_2$)	Organic C (g/100 g)	CEC ($cmol_c$/kg soil)	Clay activity ($cmol_c$/kg clay)	ESP	$EC_{1:5}$ (dS/m)	ESI
1	1993	610	260	7.6	0. 9	39	64	2.0	0.25	0.13
2	2002	630	260	6.9	0.7	38	60	2.6	0.31	0.12
3	2000	540	320	7.3	0.7	31	57	3.9	0.36	0.09
4	1993	520	320	7.7	0.6	35	67	2.4	0.14	0.06
5	1994	620	220	6.8	0.8	40	65	8.3	0.15	0.02
6	1996	520	320	6.9	0.8	36	69	1.9	0.21	0.11
7	1996	680	210	7.0	0.9	89	131	0.4	0.10	0.25

1999, cotton was sown with no-tillage into standing wheat stubble.

Site 2: irrigated field (D1) at ACRI, Narrabri, NSW

The experimental treatments, all sown on 1-m permanent beds, were: cotton–cotton; cotton–vetch (*Vicia* spp.); cotton–wheat, where wheat stubble was incorporated into the beds with 1 or 2 passes of a disc-hiller; and cotton–wheat–vetch, where wheat stubble was retained as an *in-situ* mulch into which the following vetch crop was sown. Vetch was killed during or just before flowering through a combination of mowing and contact herbicides, and the residues retained as *in situ* mulch into which the following cotton was sown.

Site 3: irrigated on-farm site, Narrabri, NSW

The experimental treatments were: (*i*) gypsum applied at a rate of 2.5 t/ha in June 2000, and (*ii*) an untreated control. A cotton–wheat rotation was sown on 2-m permanent beds. The bed surfaces and wheat stubble remained untouched and the following cotton was sown with no-tillage. From 2003 onwards, cotton was sown after the wheat stubble in gypsum-treated plots was incorporated into the beds with a combined AerWay cultivator (AerWay, Norwich, ON, Canada: www.aerway.com/index.php?page=tillageandpagetype=ag#/1/) and sweeps, whereas wheat stubble in the previously untreated control remained undisturbed. This site was irrigated with treated sewage effluent.

Site 4: irrigated on-farm site, Warren, NSW

The experimental treatments (rotations) sown at Warren were: (*i*) continuous cotton; (*ii*) long-fallow cotton; (*iii*) cotton–high input wheat, in which wheat was sown at a rate of 100 kg/ha and fertilised with 85 kg/ha of di-ammonium phosphate and 180 kg/ha of urea at sowing; (*iv*) cotton–low input wheat, in which wheat was sown at a rate of 40 kg/ha and did not receive any nitrogen fertiliser; (*v*) cotton–green manured field pea (*Pisum sativum* L.); (*vi*) cotton–wheat–lablab (*Lablab purpureus* L.) (1993–97) followed by cotton–wheat (1997–98); and (*vii*) cotton–wheat–lablab (1993–95) followed by cotton–faba bean (*Vicia faba* L.)–lablab (1995–97) followed by cotton–faba bean (1997–98). The experimental treatments were terminated in 1998, and a cotton–wheat–summer/winter fallow–cotton sequence was sown thereafter in all plots

Site 5: irrigated on-farm site, Merah North, NSW

The experimental treatments (rotations) sown on 1-m beds between 1993 and 2000 were: (*i*) continuous cotton; (*ii*) long-fallow cotton; (*iii*) cotton–green manured faba bean until 1999, when a sorghum crop was sown during the 1999–2000 growing season; (i*v*) cotton–lablab–green-manured faba bean (1993–94) followed by cotton–unfertilised wheat (1994–2000); (*v*) cotton–lablab; and (*vi*) cotton–fertilised lablab (with phosphorus and potassium removed by cotton replaced as fertiliser). The experimental treatments were terminated in 2000 and a cotton (2000–01)–wheat (2001)–sorghum (2001–02)–winter fallow (2002)–cotton (2002–03)–wheat (2003)–summer and winter fallow (2003–04)–cotton (2004–05) sequence was sown in all plots

Site 6: rainfed on-farm site, Warra, Qld

The experimental treatments (rotations) sown with zero tillage on the flat between 1996 and 2005 were: (*i*) continuous cotton; (*ii*) cotton–sorghum (*Sorghum bicolor* (L.) Moench.); (*iii*) double-cropped cotton–wheat; (*iv*) double-cropped cotton–chickpea (*Cicer arietinum* L.)–summer fallow–wheat; and (*v*) cotton–fallow–wheat–fallow.

Site 7: rainfed on-farm site, Emerald, Qld

After beds and furrows were established with a combination of intensive tillage practices, they were managed as permanent beds (cotton stalk pulling and mulching followed by bed renovation). The experimental treatments (rotations) implemented from 1996 to 2000 were: (*i*) early cotton sown at the start of the rainy season on 1- and 2-m beds; (*ii*) wheat (sprayed out)–early cotton on 2-m beds; (*iii*) wheat allowed to mature and harvested followed by late cotton sown midway through the rainy season on 1- and 2-m beds; and (*iv*) cotton–sorghum sown in 2-m beds. The site was deep-ripped during 2000 and all plots were sown with a cotton–wheat sequence.

Sampling and analyses

Soil was sampled from beds before or shortly after planting cotton each year. Details of sampling procedures are reported in the references cited in Table 2. Soil was sampled from either the 0–0.10, 0.10–0.30, and 0.30–0.60 m depths (sites 2, 3) or the 0–0.15, 0.15–0.30, 0.30–0.45, and 0.45–0.60 m depths (sites 1, 4, 5, 6, 7) using a stratified randomised sampling design from 4–8 locations in each plot with either a tractor-mounted soil corer or a spade. A spade was used at some on-farm sites, as the growers would not permit any sampling machinery into the field due to possible trafficking and compaction of beds. A composite sample was made up for each depth in each plot and transported back to the laboratory and air-dried.

Air-dried soil was passed through a 0.5-mm sieve and total SOC concentration determined by the wet oxidation method of Walkley and Black (Rayment and Lyons 2011). Soil clods extracted from the cores or samples taken with a spade were oven-dried for 48 h at 110°C and weighed, and volume was determined by coating in paraffin wax or saran resin and displacement in water (Cresswell and Hamilton 2002). Bulk density was estimated by dividing oven-dried clod weight, which ranged between 40 and 225 g, by its volume. In the 0–0.1 or 0–0.15 m depths (depending on the site), the volume of air-dried aggregates (1–10 mm diameter) was determined with the kerosene saturation method (McIntyre and Stirk 1954). Aggregate weights were converted to an oven-dried equivalent using an air-dry water content determined on subsamples. Bulk density of aggregates was determined by dividing the oven-dried equivalent aggregate weight by its air-dry volume, as soil shrinkage curves had indicated no significant difference in volume between air-dried and oven-dried soil (Hulugalle and Entwistle 1997). Bulk density for the 0–0.1 or 0–0.15 m depth was expressed as a weighted mean of the bulk densities of aggregates and clods (2 : 1 aggregates : clods) (Hulugalle and Entwistle 1997). Storage of SOC (‘stocks’) in any one depth was estimated as the product of bulk density, sampling depth interval, and SOC concentration. Storage of SOC was reported as that in the 0–0.6 m depth (sum of storage in all depths sampled).

Daily maximum temperature values for the previously described experimental sites and time periods (Table 2) were obtained from Patched Point data in the SILO climate database hosted by the Queensland Climate Change Centre of Excellence (www.longpaddock.qld.gov.au/silo). As noted previously, the relationship between soil carbon storage and average maximum temperature was hypothesised to be best described by Gaussian or bell-shaped curves (Gendugov *et al.* 2011). Stocks of SOC and average annual maximum temperature for the 12 months before sampling were fitted to Gaussian models, and standardised residual values were determined for all data-points using regression analysis and curve-fitting software (SigmaPlot ver. 11.0; Systat Software, Inc., San Jose, CA USA; www.sigmaplot.com). Where data-points with standardised residual values >|2| were present, they were excluded and the regression was repeated as before. Fit of the data to the models was further tested with analysis of variance, R^2, the Durbin–Watson statistic, and the constant variance test (SigmaPlot ver. 11.0).

Results and discussion

Average ambient temperatures

Long-term averages (1911–2011) showed that average maximum (T_{max}) and minimum (T_{min}) temperatures were in the order: Macquarie Valley (site 4) < Namoi Valley (sites 1, 2, 3, 5) < Darling Downs (site 6) << Queensland Central Highlands (site 7) (Table 2). Similar trends were present during the periods between 1993 and 2010 when soil was sampled from the experimental sites. The decrease in both T_{max} and T_{min} with increasing distance on moving south from the equator and the Tropic of Capricorn, which is just north of Emerald (site 7), is caused by factors such as geographical variations in the amount of solar energy that reaches the surface, rainfall distribution, and ocean and atmospheric circulation patterns (Kottek *et al*. 2006; BOM 2011; Ritter 2011).

Soil organic carbon storage

Average SOC storage in the 0–0.6 m depth was highest in the Black Vertosol at Emerald (site 7) and lowest in the Grey Vertosol that was irrigated with treated sewage effluent at Narrabri (site 3) (Fig. 1). At other sites, values were generally comparable and ranged from 65 to 85 t C/ha. Variations in SOC storage among all sites were significantly ($P < 0.05$) related to soil parameters such as clay concentration ($R^2 = 0.51$**), clay activity ($cmol_c$/kg clay, $R^2 = 0.56$**), and cation exchange capacity ($cmol_c$/kg soil, $R^2 = 0.56$**). Climatic parameters such as T_{max} and rainfall at rainfed sites (sites 6 and 7) but not irrigated sites (sites 1–5) were also related to SOC storage. As rainfall and T_{max} were highly correlated ($R^2 = 0.80$***) at Warra (site 6), it was not possible to separate the role of these individual parameters on SOC storage, and further analyses were discontinued. Water inputs (irrigation and rainfall) and T_{max} were not correlated at all other sites.

At most sites, 3-parameter ($y = a*\exp(-0.5*((x - x_0)/b)^2)$) or 4-parameter ($y = y_0 + a*\exp(-0.5*((x - x_0)/b)^2)$) Gaussian curves where y is SOC stocks (t/ha), x is the average annual maximum

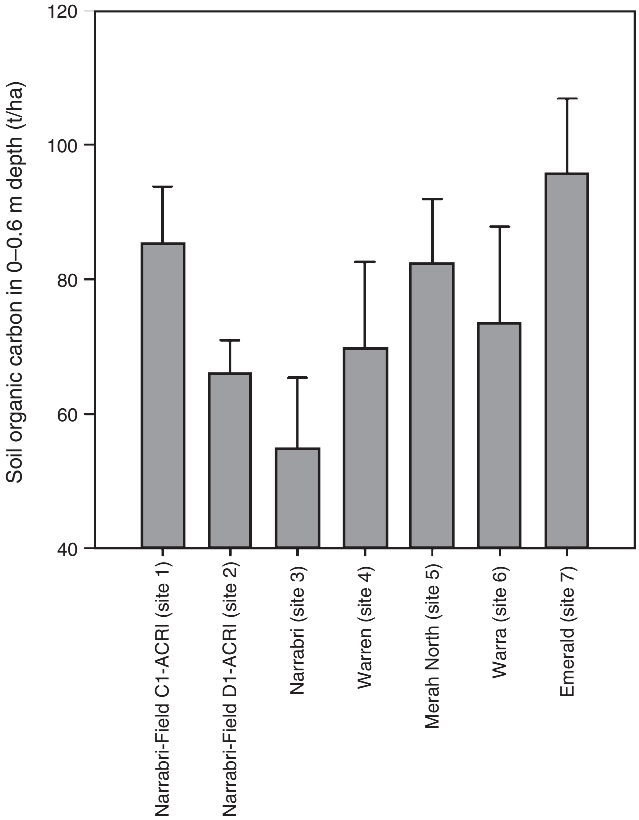

Fig. 1. Mean soil organic carbon storage in the 0–0.6 m depth of the seven experimental sites. Capped vertical lines are standard deviations. The periods under consideration are reported in Table 2.

temperature during the 12 months before sampling, and x_0 is the optimum average annual maximum temperature (with respect to SOC stocks) best described the data (Table 4, Figs 2 and 3). The exception was the Narrabri site that was irrigated with treated sewage effluent (site 3), where the relationship between SOC and T_{max} was linear (Fig. 3). Differences among experimental treatments occurred only in Field C1 at ACRI, Narrabri (site 1), where SOC storage was highest with cotton–wheat sown on permanent beds and lowest with conventionally tilled continuous cotton (Fig. 2). At all other locations, differences among treatments were absent, and values of SOC were pooled among treatments and a single curve derived.

As mentioned previously, most of the data fit Gaussian models or bell-shaped curves, typical of substrate decomposition by microorganisms (Gendugov *et al*. 2011). In our studies, the substrate was the crop residues and the product, stored SOC. These curves also indicate that carbon storage occurs at peak rates only for a very limited temperature range at any one site. Figures 2 and 3 indicate that the optimum values for carbon storage, T_{opt} (T_{max} at which carbon storage was highest), appears to be related to latitude, i.e. values increased with decreasing latitude or as one approached the equator (Table 4). The T_{opt} for the Macquarie valley, NSW (site 4), was 25.4°C, averaged 27.2°C in Namoi Valley, NSW (Sites 1, 2, 5), and was 30.1°C in the Central Highlands of Queensland (site 7). These very specific, temperature-related peaks are associated with peak activity of

Table 4. Model parameters and regression statistics for the experimental sites

CT, Conventional tillage; PB, permanent beds; SOC, soil organic carbon storage in the 0–0.6 m depth; T_{max}, average maximum temperature; T_{opt}, optimum T_{max}, temperature at which carbon storage peaks; SOC_0, initial soil organic carbon storage in the 0–0.6 m depth (intercept); s.e., standard error; *n*, no. of observations; R^2, regression coefficient; s.e.e., standard error of estimate; *$P<0.05$, **$P<0.01$, ***$P<0.001$

Site	Location	Best-fit model	Model coefficients				Regression statistics		
			a ± s.e.	b ± s.e.	T_{opt}	SOC_0	R^2	*n*	s.e.e.
1	Narrabri (ACRI, Field C1), NSW:								
	CT/continuous cotton	$SOC = a*exp(-0.5*((T_{max} - T_{opt})/b)^2)$	87.43*** ± 2.40	1.40*** ± 0.18	27.0*** ± 0.07	–	0.66**	12	5.34
	PB/continuous cotton	$SOC = a*exp(-0.5*((T_{max} - T_{opt})/b)^2)$	92.90*** ± 2.08	1.48*** ± 0.17	27.0*** ± 0.07	–	0.72**	12	4.62
	PB/cotton–wheat	$SOC = a*exp(-0.5*((T_{max} - T_{opt})/b)^2)$	95.34*** ± 2.48	1.71*** ± 0.17	27.0*** ± 0.10	–	0.51*	12	5.62
	All treatments	$SOC = a*exp(-0.5*((T_{max} - T_{opt})/b)^2)$	91.87*** ± 1.64	1.52*** ± 0.15	27.0*** ± 0.06	–	0.49***	36	6.36
2	Narrabri (ACRI, Field D1), NSW	$SOC = SOC_0 + a*exp(-0.5*((T_{max} - T_{opt})/b)^2)$	11.20*** ± 1.35	0.40*** ± 0.09	27.0*** ± 0.07	61.2*** ± 1.14	0.66***	41	3.41
3	Narrabri, NSW	$SOC = SOC_0 + a*T_{max}$	–11.31** ± 3.79	–	–	361.2*** ± 102.4	0.18**	42	9.64
4	Warren, NSW	$SOC = a*exp(-0.5*((T_{max} - T_{opt})/b)^2)$	78.92*** ± 1.08	1.49*** ± 0.05	25.4*** ± 0.02	–	0.75***	70	4.38
5	Merah North, NSW	$SOC = a*exp(-0.5*((T_{max} - T_{opt})/b)^2)$	94.26*** ± 1.72	1.88*** ± 0.15	27.9*** ± 0.09	–	0.65***	63	5.90
7	Emerald, Qld	$SOC = SOC_0 + a*exp(-0.5*((T_{max} - T_{opt})/b)^2)$	30.23*** ± 3.24	0.23*** ± 0.03	30.1*** ± 0.04	87.8*** ± 1.37	0.73***	50	5.96

different microbial populations adapted to the different geographic locations, *viz*. the Macquarie and Namoi Valleys of NSW and the Central Highlands of Queensland, which in turn may be associated with the variations in climate and soil conditions at each location (Tables 2 and 3). A similar viewpoint was proposed by Balser and Wixon (2009) in a study that included sites from Puerto Rico, California, and Alaska. Our results are contradicted, however, by Potter *et al*. (2007). They reported that in a multi-locational study of no-tilled corn (*Zea mays* L.), in which clay content of soils ranged from 12 to 77 g/100 g and rainfall from 650 to 1099 mm, soil carbon storage decreased with increasing average temperature such that when average temperature exceeded 20°C, it was negligible. They suggested that this was because of accelerated decomposition rates under warmer conditions. Although this is also shown in our results by the rapid decrease in SOC as temperature increased beyond T_{opt}, we believe that the assumption of linearity by Potter *et al*. (2007) with respect to the temperature–soil carbon relationship, a biologically driven relationship, is questionable. Furthermore, as their sites differed in texture (sandy loam to clay; clay content range 12–77 g/100 g) and climate, some confounding may have occurred.

Dalal and Carter (2000) suggested that SOC losses and, conversely, storage are dependent upon an interaction between water inputs, clay content, and temperatures such that maintenance of SOC stocks is difficult in coarse-textured soils of the tropics but may be achievable in fine-textured soils (e.g. clayey Vertosols). Table 5 indicates that SOC storage was highest (117 t C/ha) in the Central Highlands of Queensland (site 7, a fertile Black Vertosol with a high degree of soil structural stability; see Table 3 and Hulugalle *et al*. 2002*b*) and averaged 87 t C/ha among the other sites reported in Table 4 (all Grey Vertosols), ranging from 72.4 t C/ha in site 2 to 94 t C/ha in site 5. The relatively high value in site 5, despite its initially sodic nature, may be a consequence of improved aggregation resulting from regular gypsum application, salinisation due to declining irrigation water quality, and, latterly, elimination of the summer fallow (Hulugalle *et al.* 2002*a*, 2006*b*). Variation among sites was related primarily to clay activity ($R^2 = 0.78$*) (Table 3), although the influence of other factors such as length of growing season, nutrient inputs, and tillage intensity cannot be excluded (Luo *et al.* 2010; Hulugalle *et al.* 2011). The relatively low value in site 2 (72 t C/ha) compared with the other Grey Vertosols (Table 5) may be related to the low electrochemical stability index (ESI, <0.05; McKenzie 1998) in the subsurface (>0.30 m) (Hulugalle *et al.* 2012*a*), and consequently, low structural stability, which would have had a detrimental effect on SOC storage. Low structural stability may also be the reason behind the absence of a Gaussian relationship between SOC and T_{max} at site 3. The high sodium adsorption ratio (SAR) of irrigation water (Hulugalle *et al.* 2006*a*, 2011) resulted in decreases in profile ESI such that it did not exceed 0.05 in the 0–1.8 m depth by 2011 (Hulugalle *et al.* 2011). Other factors that may have contributed to the absence of a Gaussian relationship include the high nutrient loads, high alkalinity ($pH_w \geq 9$), moderate to high chloride concentration of the effluent, and overstimulation of microbial activity. Jueschke *et al.* (2008) reported that increased microbial activity and rapid decomposition of soil organic matter can occur when crops are

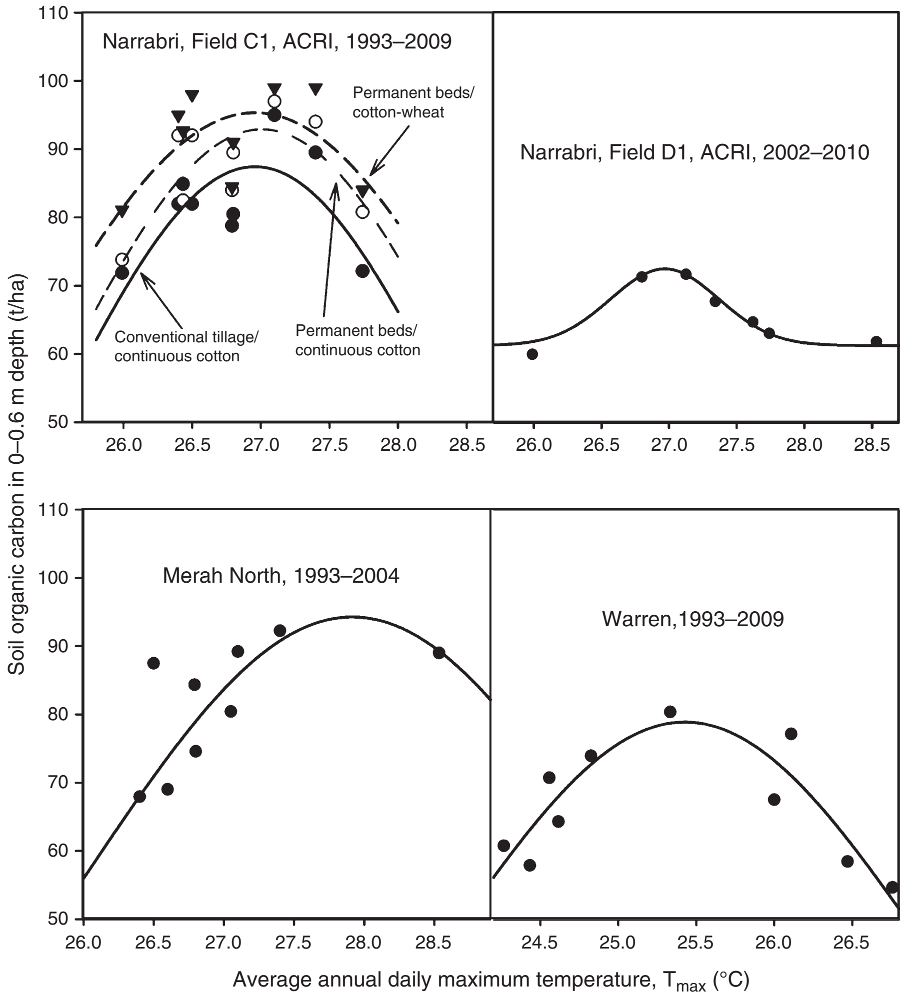

Fig. 2. Variation of soil organic carbon storage in the 0–0.6 m depth with average annual daily maximum temperature in Fields C1 (site 1) and D1 (site 2) at the Australian Cotton Research Institute (ACRI), Narrabri; Warren (site 4) and Merah North (site 5). Field C1: ●, conventional tillage/continuous cotton; ○, permanent beds/continuous cotton; ▼, permanent beds/cotton–wheat. As treatment effects were absent in other sites, results were pooled. Model parameters and regression statistics are given in Table 4.

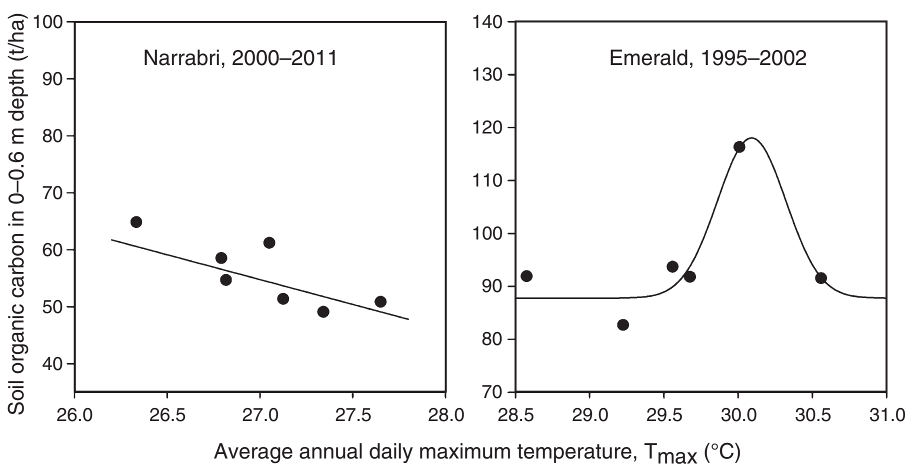

Fig. 3. Variation of soil organic carbon storage in the 0–0.6 m depth with average annual daily maximum temperature at Narrabri (site 3) and Emerald (site 7). Model parameters and regression statistics are given in Table 4.

Table 5. Optimum T_{max}, temperature at which carbon storage peaks (T_{opt}), and maximum soil organic carbon (SOC_{max}) storage in the 0–0.6 m depth for the experimental sites at Narrabri, Warren, Merah North, and Emerald estimated from the curves shown in Figs 2 and 3

Values for site 1 were derived by pooling results for all three cropping systems

Site	Location	Latitude	T_{opt} (°C)	SOC_{max} (t C/ha)
1	Narrabri (ACRI, Field C1), NSW	30°11′S	27.0	92
2	Narrabri (ACRI, Field D1), NSW	30°11′S	27.0	72
4	Warren, NSW	31°47′S	25.4	79
5	Merah North, NSW	30°11′S	27.9	94
7	Emerald, Qld	23°30′S	30.1	117

irrigated with treated sewage effluent because of its high nutrient load and dissolved organic carbon concentration.

In addition to a direct effect of T_{max}, an interaction with the cotton grown in each location on SOC storage cannot be excluded. Conaty *et al.* (2012) reported that the optimum in-crop temperature for cotton (cv. Sicot 70BRF) physiology and growth (i.e. peaks) at Narrabri, NSW (same location as sites 1 and 2) was ~28–30°C, which is very similar to the values of T_{opt} in our study. The coincidence between these values is intriguing but puzzling. Research by Hadas *et al.* (1994) has also shown that mixing of crop residues with a relatively high C/N ratio such as cotton (>60; Hulugalle and Weaver 2005) with a fine-textured soil and sufficient nutrients can facilitate microbiologically driven aggregate formation and subsequent stabilisation, and

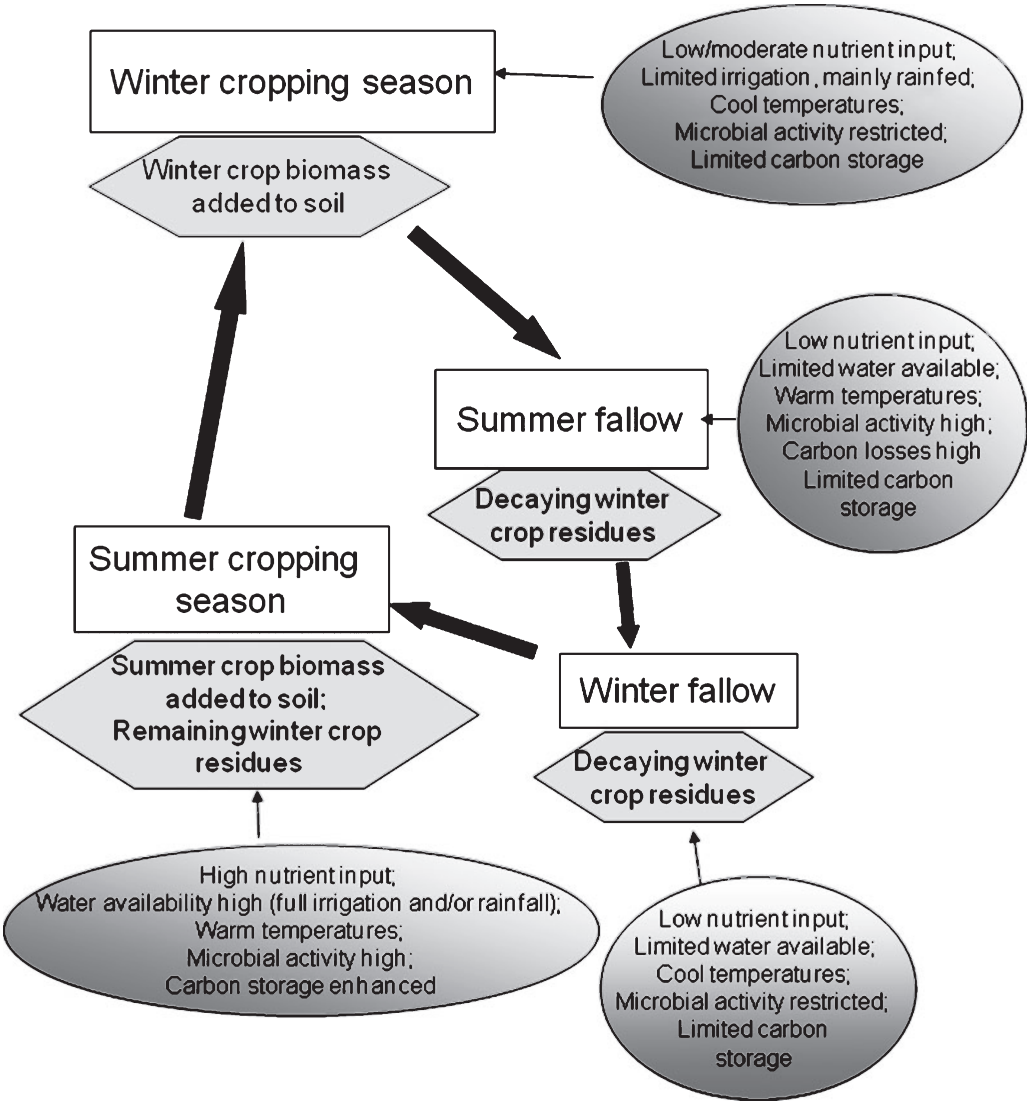

Fig. 4. Schematic outline of a proposed pathway of carbon sequestration in a summer crop (cotton)–winter rotation crop sequence. Typically, the sequence is summer crop–winter crop–summer and winter fallow–summer crop. Thick arrows indicate the chronological sequence of events, and thin arrows the inputs and processes that prevailed during each period. Note that during fallows even when water availability is high due to rainfall, restricted nutrient availability will be the major limiting factor to aggregation and carbon storage.

thus enhance carbon storage (Six *et al.* 2002). The strong influence of nutrient availability on enhancing SOC storage has also been highlighted by van Groenigen *et al*. (2006) and Kirkby *et al*. (2011). It can be surmised, therefore, that SOC storage in cotton-based farming systems may be largely driven by microbial activity and, thus, aggregation (i.e. physical protection) during the irrigated summer cropping season when warm, wet conditions are present and sufficient biomass inputs (such as stubble from previous seasons and crop roots) and nutrients are freely available, all of which are likely to enhance microbial activity. Additionally, the role of wet–dry cycles enhancing aggregation in Vertosols, and thus carbon storage, in irrigated cotton systems cannot be discounted. In contrast, a bare fallow with no biomass inputs combined with frequent tillage that disrupts aggregates can have the reverse effect and accelerate soil carbon losses. A simplified schematic outline of the suggested pathway of carbon storage in a cotton–winter rotation crop sequence is shown in Fig. 4.

Although some studies have suggested that winter rotation crops such as vetch (*Vicia villosa*, *V. benghalensis*), faba bean (*V. faba*), and wheat (*Triticum aestivum*) played a major role in sequestering carbon through biomass addition to soil (Rochester 2011), their role may be associated more with maintenance and protection of previously sequestered carbon by improving soil structure through intensifying wet–dry cycles, and increasing water storage and nutrient availability (Hulugalle and Scott 2008). This may explain why, compared with cotton monoculture, sowing different rotation crops did not improve soil carbon stocks (Hulugalle *et al.* 1998, 1999, 2002*a*, 2002*b*, 2006*b*, 2007; Hulugalle 2000; Hulugalle and Scott 2008). Biomass of winter crops may, however, contribute to soil carbon through management systems such as permanent beds, in which crop residues remain relatively intact, undisturbed, and *in situ* into the next summer (Hulugalle *et al.* 2012*b*). It should be noted that, although the summer crop in our discussion is cotton, other commonly grown summer crops such as sorghum (*Sorghum bicolor* (L.) Moench) or corn (*Zea mays* L.), which can produce more above- and below-ground biomass than cotton, may be more effective in storing carbon in soil.

Conclusions

Variations in carbon storage of Vertosols sown with cotton-based farming systems with average ambient maximum temperature were described by Gaussian models or bell-shaped curves, which are characteristic of microbial decomposition. Carbon storage occurred at peak rates only for a very limited temperature range at any one site, with these temperatures increasing with decreasing distance from the equator. These findings suggest that the decrease or absence of change in soil carbon storage with time reported in many Australian studies of annual cropping systems may be due to carbon storage occurring within a limited temperature range, whereas intra-seasonal average maximum temperatures can range widely. Further research needs to be conducted under field conditions to confirm these observations. In particular, the impact of short-term fluctuations such as heat wave events on both short- and long-term soil carbon storage is a subject worthy of more detailed study.

Acknowledgements

Funding for this research was provided by the Cotton Research and Development Corporation of Australia (1993–2011), the Co-operative Research Centre (CRC) for Sustainable Cotton production (1996–1999), the Australian Cotton CRC (1999–2005), and the Cotton Catchment Communities CRC (2005–2011). Dr M. Braunack is thanked for his comments made during manuscript preparation.

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