Chapter 4. Effect of alternative cropping management on soil carbon concentration and stock and soil microbial biomass carbon

Abstract

Vegetable production systems rely on frequent tillage to prepare beds and manage weeds, which is known to accelerate losses of soil organic carbon (SOC) stocks. At the same time, vegetable systems are characterised by little crop residue input. Crop residue incorporation and application of organic fertilisers could be ways to counteract loss of soil organic C due to tillage. We tested this hypothesis in a field trial where the effect of sweet corn (*Zea mays* L. var. *rugosa*) residue incorporation in a corn-cabbage (*Brassica oleracea* L.) rotation using organic and conventional soil management systems (SMS) on total organic C (TOC) concentration and SOC stock were studied over/after two rotation cycles (2 years) in two contrasting soil types (a Chromosol and a Vertosol). In addition, a laboratory experiment was conducted in which 2 soil types × 2 residue treatments × 3 weed management scenarios × 3 fertiliser management scenarios were investigated with a factorial design. In the field, total organic C concentration was increased ($P < 0.001$) by 6.5 % in the 0-0.1 m depth by incorporating shredded residue; however the effect of SMS was inconsistent. The Vertosol consistently had higher ($P < 0.001$) TOC concentration than the Chromosol. The laboratory experiment confirmed that the use of atrazine and mineral fertiliser in the conventional SMS in the field experiment could have no significant effect on TOC, whereas both the organic fertiliser and simulated tillage affected the organic SMS scenario ($P < 0.05$). Organic fertiliser application may, therefore, balance the C lost through tillage. There was positive but weak correlation ($r^2 = 0.37$) between TOC and microbial biomass C (MBC) across the two soil types. Soil basal respiration and MBC data showed that soil's biological fertility can be improved by incorporating residues and by combining residue incorporation with organic fertiliser. Under irrigated field conditions, residue incorporation at a rate of 14.8 Mg/ha/year in soil can accumulate an average of 0.48 and 0.61 Mg C/ha/year for Chromosol and Vertosol, respectively. The observed short-term gains have potential to translate into long-term C sequestration if sweet corn is rotated with vegetable crops and residue is incorporated into soil. Moreover, these practices may be an option to counteract the loss of C due to multiple tillage operations that vegetable systems, especially organic ones, routinely use.

4.1 Introduction

Owing to generally semi-arid climatic conditions, high temperatures and prolonged dry periods, plant primary productivity in Australia is frequently sub-optimal and thus, return of crop residues and accumulation of soil organic carbon (SOC) in soil is lower than that reported for wetter and colder regions of the world (Kern and Johnson 1993, Webb 2002, Sanderman *et al.* 2010). Dryland farmers of north-western New South Wales (NSW), Australia may not even expect to sequester atmospheric C into soil in short-to-medium term (< 20 years) (Young *et al.* 2009, Wilson *et al.* 2011). There is, therefore, a need for research into alternative management practices that facilitate SOC storage in soil such as residue retention and organic soil management system (SMS) under irrigation.

Concerns about declining SOC and increased greenhouse gas emissions due to farming practices such as intensive tillage, excessive rates of N fertiliser and bare fallows have encouraged adoption of conservation agricultural practices such as no-tillage, crop rotations and residue retention (Johnson *et al.* 2007, Smith *et al.* 2008, Luo *et al.* 2010b, Sanderman *et al.* 2010). However, whilst no-till farming is suited for broadacre crops it is unsuitable for most vegetable crops. The latter rely on tillage to perform basic management operations like preparation of beds and management of weeds. These tillage operations disrupt soil aggregates exposing the physically protected soil organic matter (SOM) leading to loss of SOC (Angers *et al.* 1993, Six *et al.* 1999, von Lützow *et al.* 2006) and lead to declines in soil productivity. Carbon input through crop residue incorporation could be one way to balance this loss and avoid SOC decline (Luo *et al.* 2010b) in a system where tillage is essential.

Organic vegetable systems rely on tillage for weed control, whereas conventional systems use herbicides to manage weeds (Bond and Grundy 2001, Bàrberi 2006, Chirinda *et al.* 2010). In addition, organic SMS use organic sources, such as crop residue and compost, for fertilisation but conventional SMS use mineral fertilisers as a main source of crop nutrition (Mondelaers *et al.* 2009, Chirinda *et al.* 2010). These management differences have a direct impact on the C balance of each system. Soil organ C in organic systems is generally reported to be higher that in the conventional systems (Clark *et al.* 1998, Wells *et al.* 2000, Mancinelli *et al.* 2010), although in some studies no such differences were detected (Leifeld *et al.* 2009, Hathaway-Jenkins *et al.* 2011). Hence, distinction between organic and conventional systems is still not clear even though the former rely heavily on organic materials for crop nutrition and thus, are claimed to store more SOC. Carbon sequestration involves net transfer of atmospheric C into land and addition of organic materials in soil is just transfer of C from one location to another

(Powlson *et al.* 2011). So sequestering atmospheric C as plant biomass and returning the biomass to soil may help the net transferring.

Whether organic or conventional, crop residue management (RM) plays an important role in maintaining SOC in horticulture, especially where annual crop rotations rely on frequent tillage. The residue management options include removal from the field, incorporated into the soil, burned *in situ*, composted, or used as mulch for succeeding crops (Wilhelm *et al.* 2004, Yadvinder *et al.* 2005). Stubble retention, incorporation and burning are, however, the main three stubble management practices in Australian conditions (Valzano *et al.* 2005). Retention of crop residue can help increase yields, improve soil nutrients and conserve soil water for semi-arid conditions (Wilhelm *et al.* 2004, Johnson *et al.* 2006). Vegetable systems are vulnerable to rapid declines in SOC as they are characterised by very little crop residue input and heavy reliance on tillage (Jackson *et al.* 2004, Chan *et al.* 2007). We examined the hypothesis that vegetable systems could be made more resistant to the effects of tillage on SOC decline by including a high-residue grain crop of sweet corn (*Zea mays* L. var. *rugosa*) in the rotation with cabbage (*Brassica oleracea* L.) through a two-year field trial. Since the type of tillage determines the rate SOC breakdown whilst crop residue management determines the rate of organic C input to a system (Liu *et al.* 2009, van Groenigen *et al.* 2011), the weed management (tillage in organic SMS and herbicide in conventional SMS) and residue incorporation were suspected of exerting opposite influences on SOC (Luo *et al.* 2010b).

Soil respiration and microbial biomass C (MBC) are widely used measures of soil biological fertility (Dinesh *et al.* 2003, Gonzalez-Quiñones *et al.* 2011, Murphy *et al.* 2011). The magnitude of the MBC generally expresses the influence of soil type, climate, ecosystem and management practices on the growth and maintenance of soil microbes (Gonzalez-Quiñones *et al.* 2011). The MBC is the 'eye of the needle' through which all organic matter entering soil must pass through to generate energy and produce metabolites for their maintenance and growth and is subject to fast turnover (Martens 1995) and so the magnitude of MBC may be a surrogate measure of labile C in the soil. In the process, micro-organism plays source/sink role of C and nutrients and determines immobilisation and mineralisation of nutrients for plant nutrition (O'Donnell *et al.* 2001). Usually the higher the TOC in the soil the higher would be the magnitude of MBC, but this is mainly determined by the size of labile pool of the TOC (Carter *et al.* 1999, Wang *et al.* 2003).

In this paper, we focus on the responses of sweet corn (variety: Early Leaming) residue incorporation in organic and conventional SMS (RM × SMS) in two soil types on TOC concentration, SOC stock, basal respiration and MBC; and also tease out confounding factors of conventional and organic SMS in the field experiment through a laboratory experiment. Incorporating shredded corn in soil by tilling changes the particle size distribution of stover and increases its contact surface area with soil, enhancing microbial colonization and the exchange of water and nutrients (Guérif *et al.* 2001). We balanced quantities of N, P and K nutrients supplied (Hoffmann *et al.* 2006) by organic and mineral fertilisers for both SMS since comparative studies on conventional and organic farming rarely balance the nutrient inputs in farming systems research (Wells *et al.* 2000, Leifeld *et al.* 2009). The specific objectives were to examine:

1. effect of SMS (conventional and organic) with two corn residue management practices (incorporation = +RES or removed = -RES) on the TOC concentration and SOC stock,
2. verify the confounding factors of conventional and organic SMS in the field experiment with the help of an incubated experiment in laboratory, and
3. effect of treatments on the basal respiration and soil microbial biomass.

4.2 Materials and methods

4.2.1 Field experiment

Experimental design

An SMS field trial was conducted over 24 months at two cropping sites in the Armidale area of NSW, Australia on two contrasting soil types: a mottled, dystrophic, Brown Chromosol, medium, loamy, non-gravelly (referred to hereafter as Chromosol) and a haplic, self-mulching, Black Vertosol, very fine (referred to hereafter as Vertosol) (Isbell 2002). These correspond to Alfisol and Vertisol, respectively, in the USDA classification (Soil Survey Staff 2010). The coordinates for the Chromosol site are 30° 29.23′ S and 151° 38.08′ E at an elevation of 1,011 m and that of the Vertosol site are 30° 28.55′ S and 151° 38.93′ E at an elevation of 1,077 m. The two sites were about 2 km apart. The experiment commenced in December 2009 and ended in December 2011 completing four cropping seasons. A completely randomized two-way factorial design was implemented and each treatment had four replications. As described in section 3.2.2, sweet corn (summer) and cabbage (variety: Sugarloaf) (winter) rotation with two SMS (organic or conventional) with two residue management practices were used. Corn was fertilised in organic and conventional SMS at the recommended rate of 200:50:40 kg/ha N:P:K (NSW DPI 2009) and the cabbages with 120:65:45 kg/ha N:P:K (NSW DPI 2006). Corn stover was shredded mechanically (Figure 4.1 and Figure 4.2), spread evenly across the +RES plots at 14.8 Mg dry weight/ha (estimated average yield) and incorporated using rotary hoe to a depth of 0.15-0.2 m. Average C input through corn stover was 6.1 and 6.2 Mg/ha for 2010 and 2011, respectively. The stover had the average C:N ratios of 43:1 in 2010 and 53:1 in 2011. Other details of the experiment are presented in Chapter 3.

Soil samples were collected on 11 December 2009 (baseline), 15-16 March 2010, 15-16 October 2010 and 29-30 December 2011 to the depth of 0.3 m with a 0.1 m interval. Hereafter, these sampling dates are referred to by month and year only. Average baseline data of the soils from three 0.1 m segments from 16 plots per site is presented in Table 4.1. Other characteristics of soil to the depth of 0.1 m are presented in Chapter 3.

Table 4.1. Total organic C, total N, pH & EC for the three depths of the two soil types (n = 16).

Soil type	Depth (m)	TOC (g/kg)	TN (g/kg)	$pH_{1:5}$ (H_2O)	$EC_{1:5}$ (dS/m)
Chromosol	0-0.1	12.8	1.24	5.25	0.124
	0.1-0.2	8.5	0.91	5.26	0.072
	0.2-0.3	4.1	0.46	6.11	0.034
Vertosol	0-0.1	24.7	2.10	5.50	0.097
	0.1-0.2	16.8	1.49	5.49	0.091
	0.2-0.3	11.1	0.97	6.07	0.066

Figure 4.1. Shredding of corn residues for with residue (+RES) plots at the Vertosol site.

Figure 4.2. The size of shredded residues for incorporation in soil is shown.

Determination of BD for SOC estimation

In each plot, soil samples were collected from four random spots to a depth of 0.3 m with a corer (internal radius = 25 mm). Then the cores were divided into three depths with 0.1 m interval and bulked for each interval to make a representative sample and hence the core volume of 0.0008 m^3 (785,720 mm^3) was used to estimate bulk density (BD). Samples were dried at 40°C for 48 hours and sieved through < 2 mm sieve. Mass of fine earth (< 2 mm fraction) was calculated on oven-dry basis by correcting for the moisture content in the air-dry soil. The mass of fine earth was corrected by subtracting the mass of gravel (> 2 mm) from total volume of sample in each representative sample. The volume of gravel was calculated by assuming average density of gravel as 2.65 Mg/m^3 (Holmes *et al.* 2011) and the weighed mass of gravel. The calculated volume of gravel was subtracted from the total volume of each representative sample to derive the effective volume for fine earth only. Therefore, BD of fine earth portion was calculated on equivalent soil mass and equivalent soil volume basis as shown in Equation 1. Effect of treatment on the mass and volume corrected BD was then assessed statistically.

$$BD_{fe} = W_{fe}/(V-V_{cf}) \qquad (1);$$

where BD_{fe} is bulk density of fine earth (< 2 mm) in Mg/m^3, W_{fe} is weight of fine earth in Mg, V is the total volume of soil sample including coarse fraction in m^3 and V_{cf} is the calculated volume of the coarse fraction (> 2 mm) in m^3.

Total organic C, TN, pH and EC

The soil samples were ground to < 0.5 mm and analysed by a complete combustion method at 950°C furnace by LECO for determination of total organic C and N. The pH of soil was acidic and so $CaCO_3$-C was not determined. The total C determined by LECO (TruSpec Carbon and Nitrogen Analyser, LECO Corporation). was, therefore, assumed to be as the TOC concentration in the soil. Soil pH and EC were analysed on 1:5 soil:water suspension using electrode method (Rayment and Higginson 1992).

Determination of SOC stock

A depth of 0.3 m is the standard reporting depth under the National Greenhouse Gas Inventory guidelines (McKenzie *et al.* 2002) for estimation of SOC stock in Australia. This is similar to the minimum sampling depth generally recommended by the Intergovernmental Panel on Climate Change (IPCC 2006). Differences in BD arising from heterogeneous presence of gravel and stones (> 2 mm) lead to a different mass of fine earth being sampled to any fixed depth, which confounds in estimating SOC stock (Holmes *et al.* 2011) as coarse fractions like gravel do not contain C. To avoid such discrepancies, mass and volume of coarse fraction needs to be corrected while calculating BD of fine earth (Holmes *et al.* 2011). Accordingly, SOC stock in Mg/ha for each 0.1 m segment was estimated using the fixed depth method as (Equation 2),

$$\text{SOC (Mg/ha)} = BD_{fe}\,(\text{Mg/m}^3) \times 10{,}000\ \text{m}^2\ (\text{area}) \times 0.1\ \text{m (depth)} \times \text{TOC \% (LECO)} \qquad (2).$$

The SOC stock for the 0-0.3 m depth was calculated by summation of the stocks for the three segments.

Soil basal respiration and MBC

Soil basal respiration and MBC was determined for the air-dry soil samples from the top 0-0.1 m depth only collected on 11 December 2009 (baseline), 15-16 March 2010, 15-16 October 2010 and 29-30 December 2011. Four replications for each treatment were used from both soil types. For the baseline, samples from the four adjacent plots were bulked together whereby four bulked representative samples were made from the 16 plots at each site. Soil MBC of air-dried soil and moist soil are highly correlated and are similar in values (Franzluebbers *et al.* 1996, Mondini *et al.* 2002) if measured after about 2 days pre-incubation. Therefore, the sieved (<2mm) air-dried soil samples were moistened and pre-incubated at 20°C for 48 hours to stabilise soils for the determination of basal respiration and microbial biomass C. Soil samples were moistened and adjusted to 75% field capacity prior to measurement of soil respiration. Approximately 80 g moistened soil in respirometer pots were placed in a water bath at 20°C in a Respicond® respirometer (Nordgren Innovations AB, Umea, Sweden) for 48 hours and evolution of CO_2 (mg CO_2/hr/100 g DM soil) was measured automatically based on the rate of changes in conductance of 0.6 M KOH traps kept within each pot.

First, average basal respiration was measured for 48 hours. Then microbial biomass was determined by the Substrate-Induced Respiration method (Anderson and Domsch 1978) whereby the increase in respiration rate over 24 hours after addition of substrate (0.22 g glucose /pot) was used to calculate the amount of microbial biomass C in soil (mg C/100 g DM soil).

4.2.2 Laboratory experiment

Experimental set up and design

The experiment was set up in a factorial design with 2 soil types × 2 residue treatments × 3 weed management scenarios × 3 fertiliser management scenarios as shown in Table 4.2. The layout was completely randomized with four replications. The SMS in the field experiment represented both fertiliser management and weed management wherein the organic SMS corresponded with the application of organic fertiliser and soil cultivation as a means to manage weeds; and the conventional SMS corresponded to the application of mineral fertilisers and herbicide application as a means to manage weeds (Bond and Grundy 2001, Chirinda *et al.* 2010). To be able to separate the effect of these confounding factors, SMS in the laboratory experiment was divided into two general groups of fertiliser and weed managements. Fertiliser management was further sub-divided into three types: without fertiliser (No fert), mineral fertiliser (Min fert) and organic fertiliser (Org fert). In a similar fashion, weed management was sub-divided into three types: without weed management (None), atrazine ($C_8H_{14}ClN_5$) herbicide application (Herbicide) and soil sieving to simulate tillage (Tillage). These combinations were applied to both with and without residue (+RES or -RES) treatment for both the Chromosol and Vertosol soils. The incorporated sweet corn residue was ground to < 4 mm. The average C:N ratio of the residue was 34:1.

Table 4.2. Fertiliser and weed management combinations with (+RES) and without (–RES) residue. None = without weed management, Herbicide = atrazine applied, Tillage = sieved to simulated tillage, No fert = without fertiliser, Org fert = organic fertiliser and Min fert = mineral fertiliser.

Residue management	Fertiliser management	Weed management None (-H-T)	Herbicide (H)	Tillage (T)
Residue incorporation (+RES) 3.17 g C/pot	No fert (-O-M)	-H-T-O-M 1	-O-M+H-T 2	-O-M-H+T 3
	Org fert (O) 0.5 g C/pot	+O-M-H-T 4	+O-M+H-T 5	+O-M-H+T 6
	Min fert (M)	-O+M-H-T 7	-O+M+H-T 8	-O+M-H+T 9
Without residue (-RES) 0 g C/pot	No fert (-O-M)	-H-T-O-M 10	-O-M+H-T 11	-O-M-H+T 12
	Org fert (O) 0.5 g C/pot	+O-M-H-T 13	+O-M+H-T 14	+O-M-H+T 15
	Min fert (M)	-O+M-H-T 16	-O+M+H-T 17	-O+M-H+T 18

We excluded 'Min fert + Herbicide' (cells 8 and 17) and 'Org fert + Herbicide' (cells 5 and 14) treatments from the experiment as there would be only very negligible quantity, i.e. less than 0.5 kg C/ha (428.16 g C/ha) of C input through atrazine (as 480 g/L of S-triazine as active ingredient) application at 2 L/ha rate. The effect of atrazine was expected to be established from the differences in TOC concentrations between 'No fert + None' and 'No fert + Herbicide' treatments in both residue (±RES) treatments. 'Org fert + Herbicide' treatment did not represent any meaningful organic SMS treatment in the field experiment to isolate the confounding factors.

Carbon inputs from residue and fertilisers

Nutrient input through either mineral or organic fertilisers were 80:35:25 N:P:K mg/pot which was calculated from 200:50:40 N:P:K kg/ha (NSW DPI 2009) applied for the crop of sweet corn in the field experiment. Input of C via organic fertilisers in the field experiment was 985 kg/ha and this translated to 0.50 g (495 mg) C/pot in the laboratory experiment. Input of C from incorporated residue was 3.17 g C/pot based on 15 Mg/ha residue (oven-dried equivalent) incorporated in the field experiment. Both mineral and organic fertilisers were finely ground (< 0.5 mm) and incorporated into soil by mixing thoroughly.

Pre-incubation

Five hundred (Vertosol) and 600 (Chromosol) grams (oven-dried equivalent) of air-dried and sieved (< 2 mm) soil were weighed into 8.6 cm diameter polythene pots to a depth of ~0.1 m and treatments applied. Due to different bulk densities, these weights gave similar soil volumes in the pot. The soils were pre-incubated at 25ºC for four months to allow decomposition of the incorporated residue and fertilisers. During pre-incubation, water was applied once every two weeks for Vertosol and once every six days for Chromosol to raise soil moisture levels from wilting point (-1500 kPa) to field capacity (-33 kPa). Particle size distribution of the two soils enabled their hydraulic characteristics to be estimated with the pedotransfer functions of Vervoort *et al.* (2006) for Vertosols and Minasny (2006) for Chromosols. Estimated water content at field capacity and wilting point for Vertosols were 41.4 and 26.3% (v/v), respectively and that of Chromosols were 16.4 and 7.9% (v/v), respectively.

Simulating weed management scenarios

At the end of pre-incubation, i.e. when treated soils approached wilting point, they were sieved to disturb soil or simulate tillage (Roberts and Chan 1990, Calderón *et al.* 2000, Kristensen *et al.* 2003) through a 4 mm mesh. This was intended to simulate an intense tillage event. There were two sieving events that represented two cultivations in the field experiment with the second sieving performed 15 days after the first. To avoid smearing and for practical convenience, soils were sieved when the soil moisture level dropped close to wilting point. The sieving operation (on a sieve-shaker) and repacking of each sample was completed within 10 and 20 minutes for the Chromosol and Vertosol, respectively. The remaining hard clods that could not be broken by sieve-shaker were broken gently by hand or by mortar and pestle.

The aim of sieving was to simulate tillage by disturbing soil in a manner that was analogous to field tilling with a rotary hoe, a common tillage implement used in vegetable production (Henderson and Bishop 2000). Soil aggregate sizes after rotary hoeing have been reported to be 40% at $\leq$ 5 mm and 80% $\leq$ 15 mm (Braunack and McPhee 1991). The action of sieving broke up soil into smaller clods, mixed up incorporated residue and exposed soil to aeration (Dao 1998, Conant *et al.* 2007).

Atrazine was applied at a rate of at 2 L/ha (or 0.1006 parts per million) to the +Herbicide treatments at the same time as +Tillage treatments were sieved. The timing was matched to mimic coinciding of spraying time by conventional farmers with the cultivation time by organic growers to manage weeds. After simulating tillage and applying herbicide, the pots were maintained under the same pre-incubation conditions for at least 30 days from the first sieving. At the end of this period soils were air-dried, sieved (< 2 mm), ground (< 5 mm) and analysed for TOC in the LECO.

4.2.3 Statistical analysis

An analysis of variance (ANOVA) was used to assess the effects of residue incorporation, SMS and soil type, soil depth and sampling time on the TOC, TN, soil pH, EC and subsequently mentioned parameters using R version 2.11 (R Development Core Team 2010). Soil basal respiration and microbial biomass C was determined for top the 0-0.1 m segment only and so depth was not a factor in ANOVA. Whilst bulk density and soil C stock was assessed to the depth of 0.3 m for the December 2011 samples only, i.e. after two years from the commencement of the experiment.

For the laboratory experiment, ANOVA was performed to analyse the effect of residue, soil type, and weed and fertiliser management scenarios on TOC. Variances were checked by plotting residual vs. fitted values to assess normality assumptions of ANOVA for all statistical analysis. Data were transformed to stabilise variance where data deviated from fulfilment of normality assumptions. P-values < 0.05 were considered significant. Mean values of data are presented along with 95% confidence intervals (standard error × 1.96) to separate significantly different means (Brandstätter 1999).

4.3 Results

4.3.1 Field experiment

The summarised significant results of ANOVA for TOC and TN concentrations, soil pH and EC for the four sampling times including the baseline in mid-December 2009 are presented in Table 4.3.

Soil pH and EC

Soil pH was influenced by sampling time, soil type and depth of the soil and the significant interactions were: time × depth, residue × depth, time × soil type, depth × soil type and time × depth × soil type (Table 4.3). Soil EC was influenced by sampling time, SMS, residue, soil type and depth and there were a number of significant interactions (Table 4.3). The treatment means of soil pH and EC with respective 95% confidence intervals are shown in Table 4.6 and Table 4.7, respectively.

The highest increase in soil pH, i.e. 9%, occurred from the baseline to December 2011 and there was 5% increase each to October 2010 and March 2011 from the baseline, on average, across soil types. Between the soil types the Vertosol was 1% lower in pH than the Chromosol, across sampling times. Soil pH in top two horizons were similar, however it decreased by 10% from top two horizons to 0.2-0.3 m depth, across the two soil types.

Average soil EC increased by 4% and 2% in the residue incorporated treatments and the organic SMS compared to the treatments without residue and the conventional SMS, respectively, across soil types. Soil EC decreased over time and the decrease between 36-48% occurred from the baseline to the other sampling times. Average soil EC in the Vertosol was 46% higher than in the Chromosol. With successive increase in the depth soil EC decreased successively (by 19% from the 0-0.1 m to 0.1-0.2 m and by 26% from the 0.1-0.2 to 0.2-0.3 m) in both soil types.

TOC and TN concentrations

The main factors of time, SMS, residue incorporation, soil type and soil depth significantly influenced TOC concentration over the experimentation time of two years, as did the following interactions: time × depth, residue × depth, time × soil type, SMS × soil type, depth × soil type and time × depth × soil type (Table 4.3). The treatment means with 95% confidence intervals of the means of TOC and TN concentrations by sampling time and soil depth for the two soil types are presented in Table 4.4 and Table 4.5, respectively.

om the baseline in December 2009, TOC concentration generally increased over time mainly in the top 0-0.1 m horizon. On average, there was a 7%, 3% and 3% increases in October 2010, March 2011 and December 2011, respectively, from the baseline in the top 0-0.1 m horizon, across the two soil types. The effect of residue incorporation decreased with depth; at 0-0.1 m the residue incorporated treatment increased average TOC concentration by 7% compared to about 4% average increase in the deeper two segments, across the two soil types. This is why there was a residue × depth interaction. The SMS × soil type interaction was significant because in the Chromosol there was an average increase of TOC concentration by 7% in organic SMS compared with conventional SMS, but in the Vertosol there was no such difference. Average TOC concentration for the Vertosol was 94% higher than the Chromosol at 0-0.1 m depth, this difference increased with the increase in depth and at 0.2-0.3 m segment the average TOC concentration in the Vertosol was 156% higher than in the Chromosol. These differences produced the significant depth × soil type interaction.

Total N concentrations followed the same trend as the TOC except that time and residue × depth were not significant. There was strong correlation ($r^2 \geq 0.92$) between averaged TN and TOC over all treatment for the three depths in both soil types.

Table 4.3. Significant results from ANOVA of TOC, TN, pH and EC for the field experiment. Significance levels: *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$ and ns = not significant.

	Total organic carbon	Total nitrogen	Soil pH	Electrical conductivity[a]
T (soil sampling time)	**	ns	***	***
F (soil management system)	*	**	ns	***
R (± residue)	***	**	ns	*
S (soil type)	***	***	***	***
D (depth)	***	***	***	***
T × F	ns	*	ns	***
T × D	***	***	***	***
R × D	*	ns	*	ns
T × S	***	***	***	***
F × S	*	**	ns	**
D × S	***	***	**	***
T × D × S	*	***	***	***

[a] log transformed to stabilise variances

Table 4.4. The treatment means and 95% confidence intervals (CI) of total organic carbon (g/kg) in two soil types with depths and sampling times. Conv±RES = conventional soil management treatments with or without residue incorporation; Org±RES = Organic soil management treatments with or without residue incorporation.

Soil type	Sampling time	Depth (m)	Treatment				
			Conv+RES	Conv-RES	Org+RES	Org-RES	95% CI
Chromosol	16 Oct 2010	0-0.1	12.1	12.4	10.9	12.2	±0.64
		0.1-0.2	8.6	7.6	8.6	8.5	±0.45
		0.2-0.3	3.7	3.5	4.0	3.9	±0.24
	29 Mar 2011	0-0.1	13.7	11.7	15.0	13.7	±1.35
		0.1-0.2	7.9	7.2	9.2	8.8	±0.86
		0.2-0.3	3.5	3.6	4.3	4.3	±0.43
	30 Dec 2011	0-0.1	13.5	11.3	14.6	12.5	±1.39
		0.1-0.2	7.7	6.6	7.7	7.5	±0.51
		0.2-0.3	5.7	5.3	5.5	5.7	±0.17
Vertosol	15 Oct 2010	0-0.1	28.2	25.8	27.3	25.8	±1.18
		0.1-0.2	18.2	16.7	17.1	16.8	±0.66
		0.2-0.3	13.0	11.5	11.4	11.8	±0.72
	30 Mar 2011	0-0.1	25.8	24.2	25.4	25.3	±0.65
		0.1-0.2	16.0	14.7	16.4	15.5	±0.73
		0.2-0.3	11.3	10.5	12.1	10.8	±0.69
	29 Dec 2011	0-0.1	26.8	24.3	26.3	24.5	±1.23
		0.1-0.2	15.8	14.9	15.7	14.7	±0.54
		0.2-0.3	9.7	10.6	10.8	10.7	±0.49

Table 4.5. The treatment means and 95% confidence intervals (CI) of total nitrogen (g/kg) in two soil types with depths and sampling times. Conv±RES = conventional soil management treatments with or without residue incorporation; Org±RES = Organic soil management treatments with or without residue incorporation.

Soil type	Sampling time	Depth (m)	Treatment				
			Conv+RES	Conv-RES	Org+RES	Org-RES	95% CI
Chromosol	16 Oct 2010	0-0.1	1.17	1.20	1.30	1.25	±0.056
		0.1-0.2	0.91	0.83	0.92	0.90	±0.042
		0.2-0.3	0.42	0.40	0.44	0.44	±0.020
	29 Mar 2011	0-0.1	1.33	1.19	1.52	1.43	±0.140
		0.1-0.2	0.85	0.80	0.98	0.99	±0.090
		0.2-0.3	0.39	0.44	0.53	0.52	±0.065
	30 Dec 2011	0-0.1	1.34	1.20	1.50	1.33	±0.122
		0.1-0.2	0.85	0.71	0.87	0.84	±0.074
		0.2-0.3	0.64	0.64	0.63	0.68	±0.022
Vertosol	15 Oct 2010	0-0.1	2.36	2.21	2.30	2.21	±0.072
		0.1-0.2	1.57	1.47	1.46	1.46	±0.051
		0.2-0.3	1.06	1.00	0.96	0.99	±0.042
	30 Mar 2011	0-0.1	2.35	2.26	2.37	2.37	±0.050
		0.1-0.2	1.41	1.27	1.39	1.39	±0.060
		0.2-0.3	0.94	0.91	1.01	0.94	±0.040
	29 Dec 2011	0-0.1	2.36	2.17	2.37	2.29	±0.089
		0.1-0.2	1.41	1.32	1.39	1.27	±0.064
		0.2-0.3	0.87	0.91	0.91	0.91	±0.020

Table 4.6. The treatment means and 95% confidence intervals (CI) of soil pH in two soil types with depths and sampling times. Conv±RES = conventional soil management treatments with or without residue incorporation; Org±RES = Organic soil management treatments with or without residue incorporation.

Soil type	Sampling time	Depth (m)	Treatment				
			Conv+RES	Conv-RES	Org+RES	Org-RES	95% CI
Chromosol	16 Oct 2010	0-0.1	5.80	5.51	5.75	5.59	±0.132
		0.1-0.2	5.69	5.66	5.58	5.47	±0.095
		0.2-0.3	6.46	6.55	6.43	6.34	±0.083
	29 Mar 2011	0-0.1	5.91	5.69	5.87	5.78	±0.099
		0.1-0.2	5.83	5.74	5.70	5.69	±0.064
		0.2-0.3	6.50	6.43	6.29	6.35	±0.091
	30 Dec 2011	0-0.1	6.23	6.16	6.25	6.27	±0.047
		0.1-0.2	6.03	6.05	6.04	6.15	±0.053
		0.2-0.3	6.27	6.32	6.28	6.33	±0.028
Vertosol	15 Oct 2010	0-0.1	5.79	5.69	5.82	5.70	±0.065
		0.1-0.2	5.58	5.66	5.61	5.70	±0.052
		0.2-0.3	6.17	6.28	6.19	6.31	±0.067
	30 Mar 2011	0-0.1	5.50	5.51	5.59	5.56	±0.044
		0.1-0.2	5.70	5.71	5.65	5.70	±0.025
		0.2-0.3	6.14	6.21	6.13	6.19	±0.037
	29 Dec 2011	0-0.1	5.84	5.76	5.94	5.86	±0.071
		0.1-0.2	5.89	5.89	5.89	5.93	±0.020
		0.2-0.3	6.37	6.25	6.21	6.35	±0.074

Table 4.7. The treatment means and 95% confidence intervals (CI) of soil electrical conductivity (dS/m) in two soil types with depths and sampling times. Conv±RES = conventional soil management treatments with or without residue incorporation; Org±RES = Organic soil management treatments with or without residue incorporation.

Soil type	Sampling time	Depth (m)	Treatment				
			Conv+RES	Conv-RES	Org+RES	Org-RES	95% CI
Chromosol	16 Oct 2010	0-0.1	0.04	0.03	0.04	0.04	±0.005
		0.1-0.2	0.05	0.03	0.05	0.05	±0.007
		0.2-0.3	0.02	0.02	0.02	0.02	±0.002
	29 Mar 2011	0-0.1	0.05	0.05	0.06	0.05	±0.007
		0.1-0.2	0.03	0.03	0.04	0.03	±0.005
		0.2-0.3	0.02	0.02	0.02	0.02	±0.002
	30 Dec 2011	0-0.1	0.05	0.04	0.05	0.05	±0.004
		0.1-0.2	0.03	0.03	0.03	0.03	±0.001
		0.2-0.3	0.02	0.02	0.02	0.03	±0.001
Vertosol	15 Oct 2010	0-0.1	0.06	0.06	0.06	0.06	±0.003
		0.1-0.2	0.07	0.07	0.07	0.07	±0.003
		0.2-0.3	0.06	0.06	0.06	0.06	±0.003
	30 Mar 2011	0-0.1	0.08	0.08	0.09	0.08	±0.006
		0.1-0.2	0.06	0.06	0.06	0.07	±0.002
		0.2-0.3	0.06	0.05	0.06	0.06	±0.003
	29 Dec 2011	0-0.1	0.05	0.05	0.06	0.06	±0.004
		0.1-0.2	0.05	0.05	0.05	0.05	±0.002
		0.2-0.3	0.04	0.05	0.04	0.05	±0.003

Bulk density

Soil bulk density and SOC stocks were determined and statistically analysed for December 2011 soil samples only. BD of fine earth (< 2 mm) was significant for depth ($P < 0.05$) and soil type ($P < 0.001$) and other main terms were not significant (Figure 4.3). There was strong soil type × depth ($P<0.001$) interaction and no other interactions were significant. Due to compactness with depth, there was a general increase in the BD with depth and so the BD increased by 2.7% from 0-0.1 to 0.2-0.3 segment, on average, across the two soil types. On average, the mass and volume corrected BD of the Chromosol was 7.7% lower than that of the Vertosol.

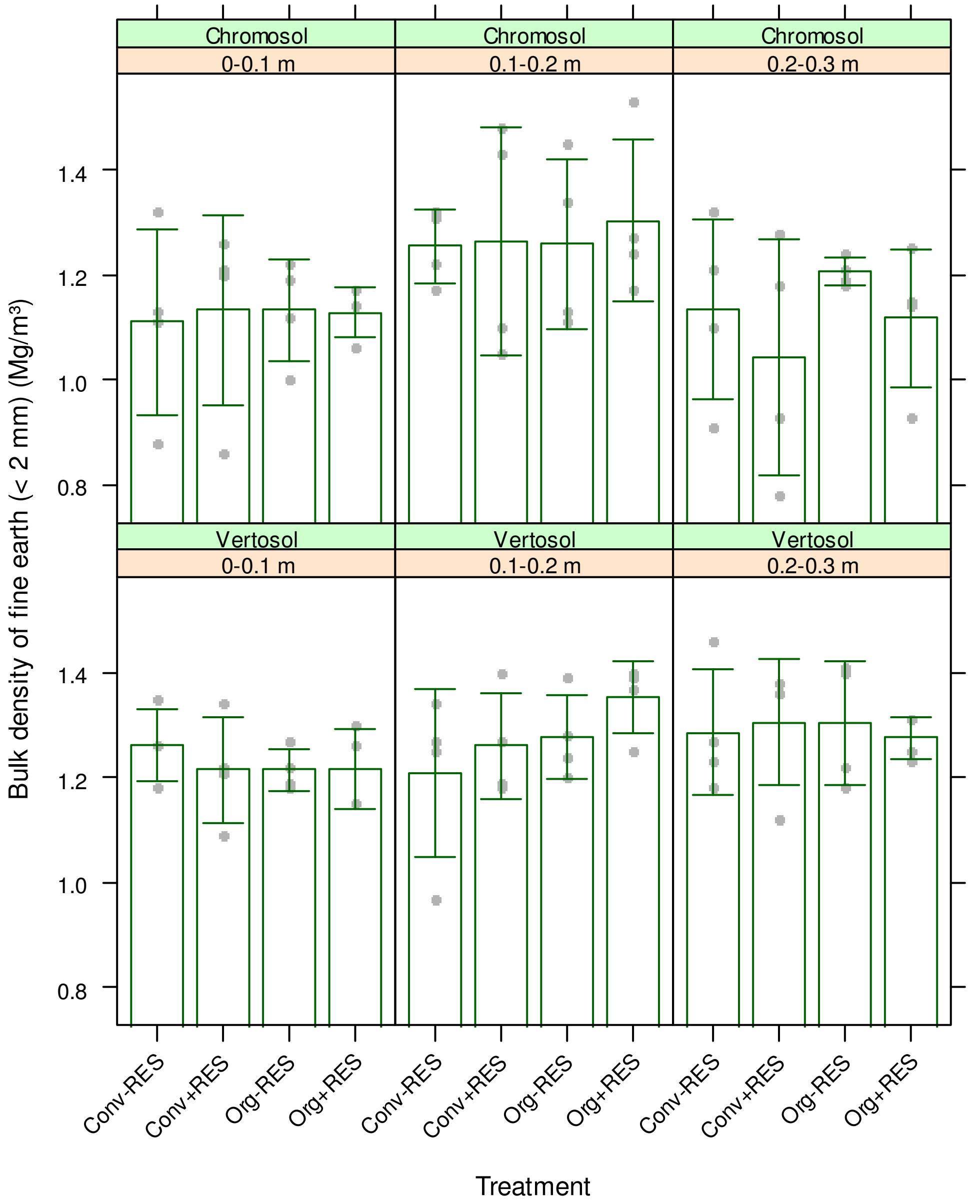


Figure 4.3. Corrected BD for > 2 mm fraction in two soil types at December 2011. The vertical bars are 95% confidence intervals of the means. Grey dots are raw data points. Conv±RES = conventional soil management treatments with or without residue incorporation; Org±RES = Organic soil management treatments with or without residue incorporation.

Soil organic carbon stock

Soil organic C stock was highly ($P < 0.001$) influenced by soil type and depth of soil and residue incorporation was significant at $P < 0.05$ (Figure 4.4). Neither the TOC concentration ($P = 0.313$) nor the SOC stock ($P = 0.156$) was significant for the SMS with regard to the samples collected in December 2011. The soil type × depth interaction was highly ($P < 0.001$) significant and depth × residue was significant at $P < 0.05$. No other factors or interactions had a significant impact on SOC stock. Generally, the SOC stock decreased with the increase of soil depth. On average, the SOC stock decreased by 37% from 0-0.1 m to 0.1-0.2 m segment, decreased by 32% from 0.1-0.2 m to 0.2-0.3 m segment and decreased by 57% from 0-0.1 m to 0.2-0.3m segment, across the two types. On average, residue incorporated treatments had 7.2% (1.096 Mg/ha) higher quantity of SOC stock in comparison to the treatments without residue to the depth of 0.3 m. It worked out to be 0.548 Mg C/ha/year when equilibria were not yet attained (0.484 and 0.611 Mg C/ha/year for Chromosol and Vertosol, respectively), which accounts for 9.12% of 6.01 Mg C/ha/year incorporated as corn residue. Average SOC stock for the Chromosol to the depth of 0.3 m was 30 Mg/ha which was less than half of 64 Mg/ha stock in the Vertosol. Therefore, Vertosol stored 112% (34 Mg/ha) more SOC stock than the Chromosol to the depth of 0.3 m.

The interaction between depth and soil type was because the Vertosol had 113%, 107% and 117% higher quantity of C stock in comparison to the Chromosol in the 0-0.1 m, 0.1-0.2 m and 0.2-0.3 m segments, respectively, on average. The difference between the Chromosol and Vertosol gets closer from 0-0.1 m to 0.2-0.3 m segment and SOC decreases with depth in both soil types. The interaction between depth and residue was because the residue incorporated treatment had ~11% higher quantity of SOC stock in the top two segments; however in the 0.2-0.3 segment the residue incorporated treatment had only ~5% lower quantity of SOC stock compared with the top two segments. The SOC stock distribution through the soil profile differed between with and without residue treatments manifesting in the significant interaction between depth and residue.

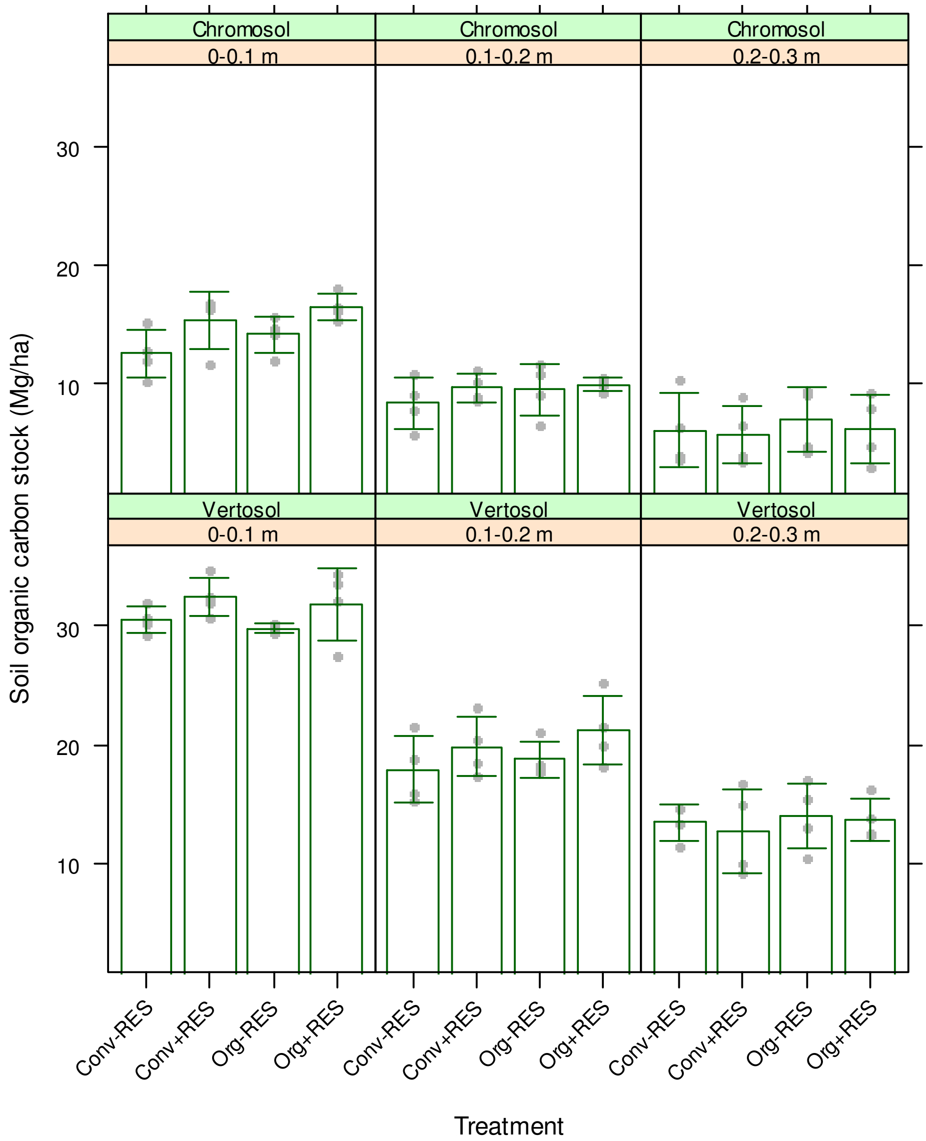


Figure 4.4. SOC stocks for two soil types as measured in December 2011. The vertical bars are 95% confidence intervals of the means. Grey dots are raw data points. Conv±RES = conventional soil management treatments with or without residue incorporation; Org±RES = Organic soil management treatments with or without residue incorporation.

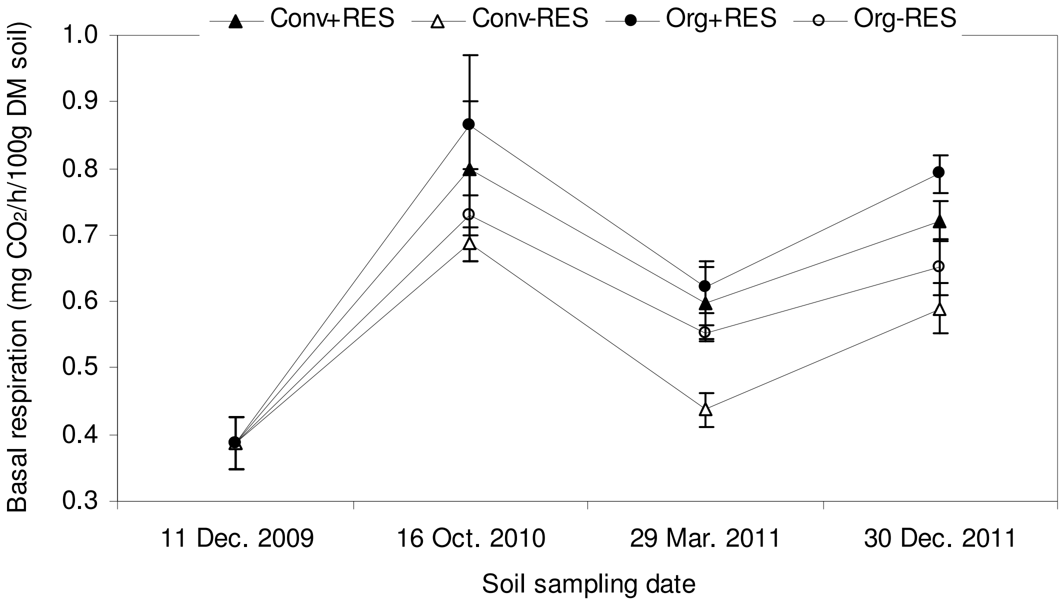
Soil basal respiration

Soil sampling time and residue incorporation had highly significant ($P < 0.001$) influence on the basal respiration of the two soil types (Figure 4.5). Soil type and SMS were not significant. The only two significant interactions were time × residue and time × soil type which were both highly significant ($P < 0.001$). From the baseline in December 2009 to the end of the experiment in December 2011, average basal respiration increased by 45%; so with time basal respiration has increased compared with the baseline data. However, from October 2010 to March 2011 there was an average drop by 27% because labile C stock could have decreased over time as no additional organic matter was added between the two measurements. On average, there was 21% increase of basal respiration in the residue incorporated treatments, due to increase in availability of substrate, in comparison to the treatments without residue across the soil types and the sampling times.

The residue incorporated treatments responded with much greater percentages of basal respiration compared with the treatment without residue at different soil sampling times; residue incorporated treatments increased average basal respiration by 83% and 63% in October 2010 and December 2011 compared with 41% and 27% increases for treatments without residue, respectively, from the baseline in December 2009.

Average increase of basal respiration in the Chromosol and Vertosol from baseline (December 2009) to October 2010 was by 99% and 34%, respectively. Likewise, average increase in basal respiration in the Chromosol and Vertosol from baseline (December 2009) to December 2011 was by 78% and 20%, respectively. The difference in the rate of increase resulted in the significant interaction between time and soil types. Although, basal respiration was positively but poorly correlated (r^2 = 0.004) to TOC concentration, data showed that basal respiration was in order: Conv-RES < Org-RES < Conv+RES < Org+RES (slightly different in Vertosol) indicating the difference in the amount available substrate for soil microbes.

A



B

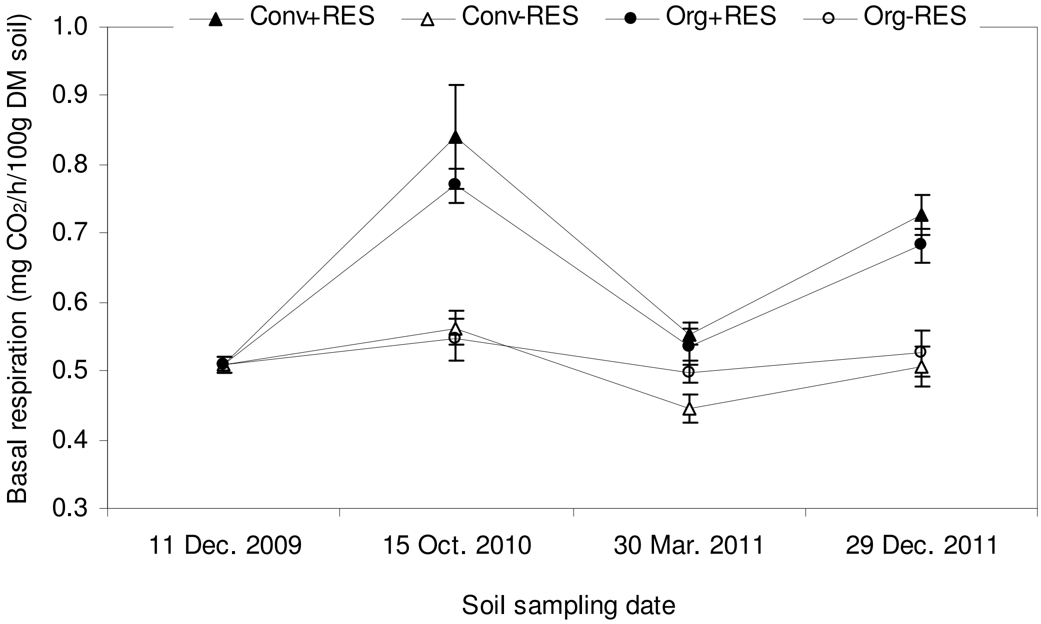


Figure 4.5. Soil basal respirations for four different sampling times. The vertical bars are 95% confidence intervals of means. A = Chromosol, B = Vertosol. Note: y-axes do not originate at '0'.Conv±RES = conventional soil management treatments with or without residue incorporation; Org±RES = Organic soil management treatments with or without residue incorporation.

Soil microbial biomass carbon (MBC)

The factors residue incorporation, soil type and sampling time had a highly significant ($P < 0.001$) effect on MBC, while SMS was significant at $P < 0.05$ (Figure 4.6). Similar to the case of basal respiration, the only two significant interactions were time × residue and time × soil type. On average, residue incorporated treatments increased MBC by 32% in comparison to the treatments without residue. Between soil types, MBC in the Vertosol was higher by 49% in comparison to the Chromosol, on average. There was a general trend of increase in MBC over time except for October 2010 to March 2011 period where MBC decreased by 15%. On average, the organic SMS increased the MBC by 8% compared with the conventional SMS due to improvement in the organic matter from organic fertiliser. Although, soil MBC was positively and weakly correlated ($r^2 = 0.37$) with TOC concentration, soil MBC was generally in order: Conv-RES < Org-RES < Conv+RES < Org+RES indicating the difference in the amount labile C.

The residue incorporated treatments responded with much greater percentages of MBC compared with the treatments without residue at different sampling times; residue incorporated treatments increased the average MBC by 104% and 139% in October 2010 and December 2011 compared with 39% and 67% increases for treatments without residue, respectively, from the baseline in December 2009.

Average increase in MBC in the Chromosol and Vertosol from the baseline (December 2009) to October 2010 was by 83% and 65%, respectively. Likewise, average increase in MBC in the Chromosol and Vertosol from the baseline (December 2009) to December 2011 was by 159% and 74%, respectively. The difference in the rate of increase has resulted in the significant interaction between time and soil type.

A

B

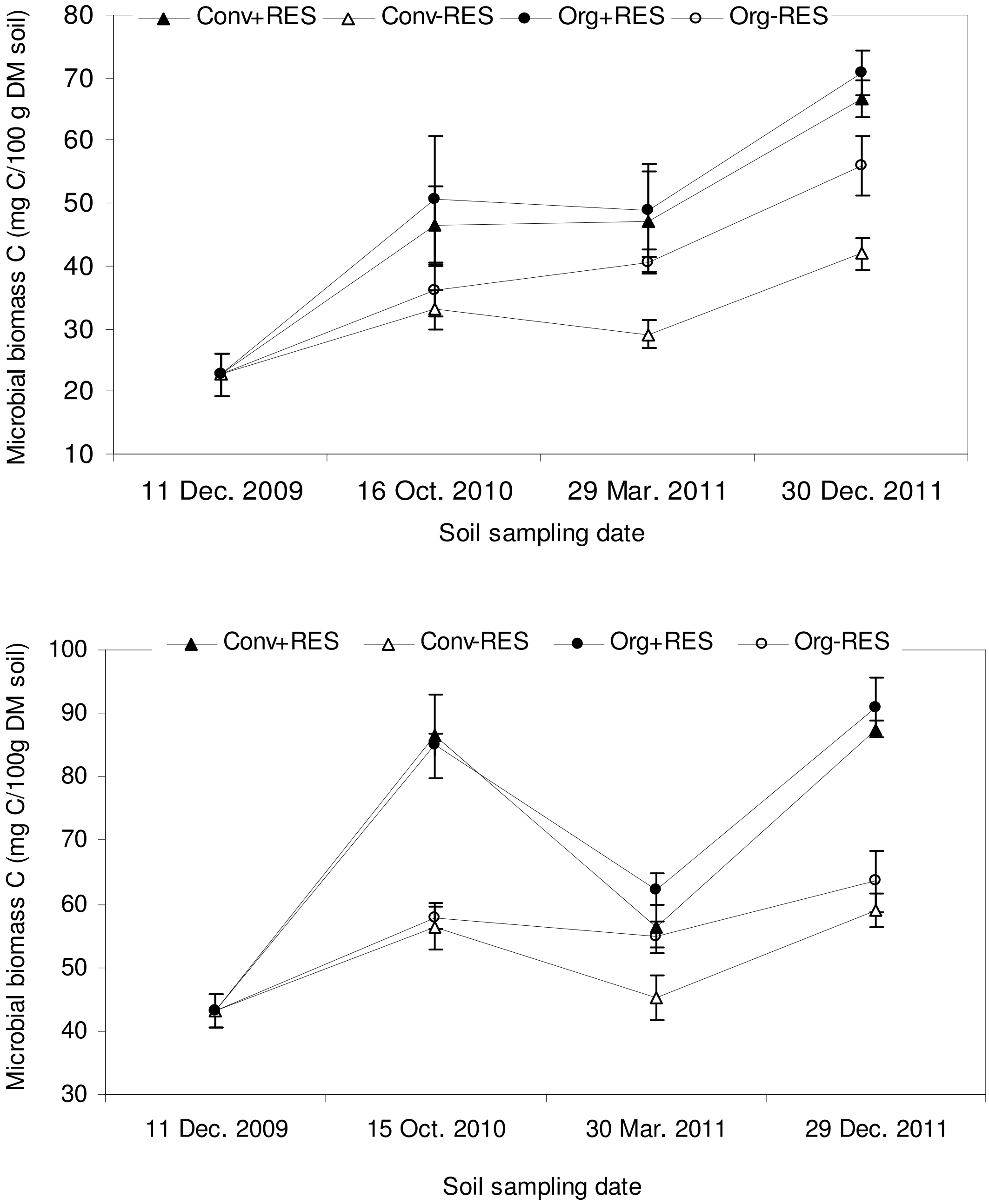


Figure 4.6. Soil microbial biomass C for four different sampling times. The vertical bars are 95% confidence intervals of means. A = Chromosol, B = Vertosol. Note: y-axes do not originate at '0'. Conv±RES = conventional soil management treatments with or without residue incorporation; Org±RES = Organic soil management treatments with or without residue incorporation.

4.3.2 Laboratory experiment

The three main treatment factors of fertiliser management, residue incorporation and soil type had highly significant ($P < 0.001$) influence on TOC concentrations whilst weed management was significant at $P < 0.05$ (Figure 4.7). The three-way interaction, weed management ×

residue × soil type was moderately significant ($P < 0.01$); the two-way interaction, weed management × residue was significant at $P < 0.05$ and other interactions were not significant.

To tease out the confounding factors at systems level, a reductionist approach was pursued to evaluate the causal effects of the various confounded management activities in the field trial on soil C changes. The use of mineral fertilisers and herbicide in conventional SMS has a potential synergistic effect and it is of interest to isolate the effect of each to account for the role of each on TOC concentration. In organic SMS, the organic fertiliser application and cultivation to manage weeds potentially counteract each other. Therefore, the weed management treatment in the laboratory experiment had three types: None (control), Herbicide and Tillage to isolate effect of each by way of the factorial design. When these three weed management types were compared within the No fert treatments, the effect of herbicide was not significantly different to the None (without weed management) treatment or the simulated tillage treatment ($P = 0.197$) for both with or without (± RES) residue, across the two soil types (Figure 4.7). Therefore, we eliminated the role of atrazine as herbicide to have any significant influence TOC concentration in conventional SMS. The differences due to residue and soil type within No fert treatment are also demonstrated by Figure 4.7.

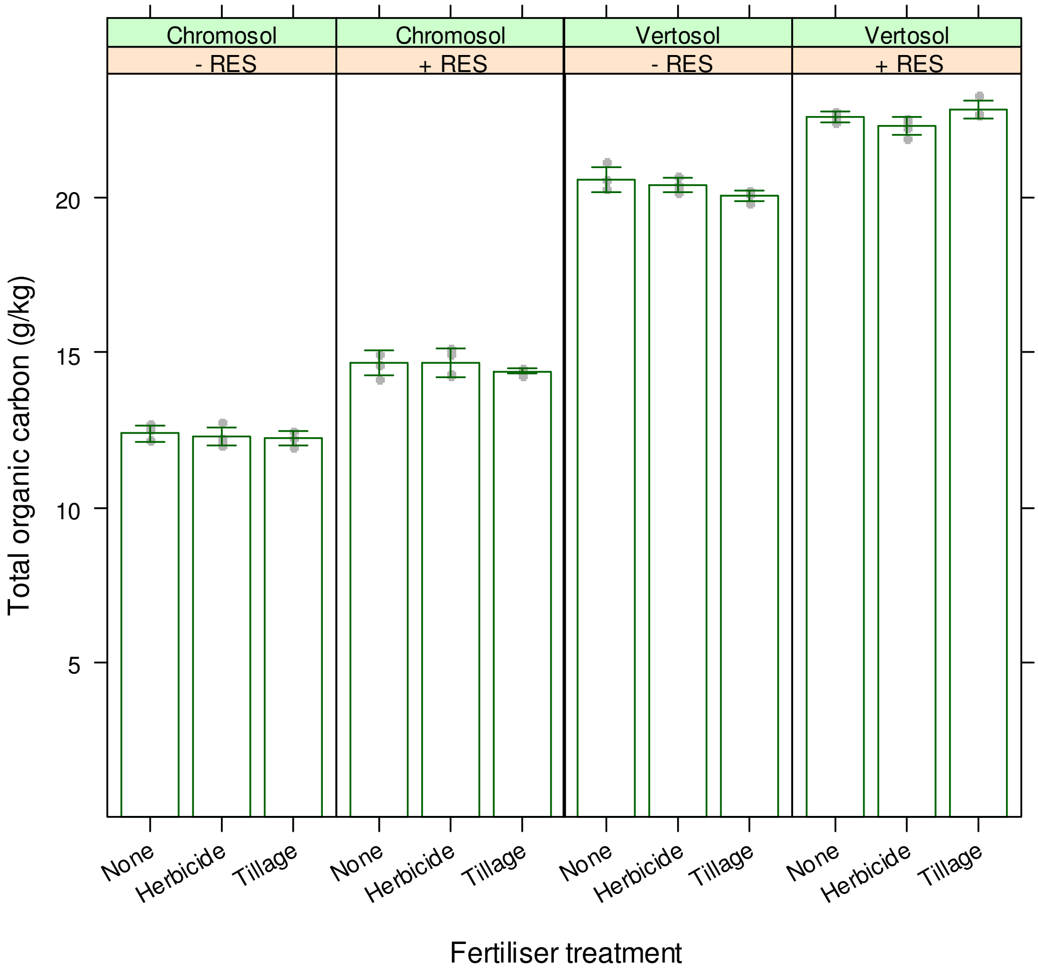


Figure 4.7. Effect of three weed management types for No fert (without fertilisers). The vertical bars are 95 % confidence intervals of means. Grey dots are raw data points. +RES = residue incorporated, -RES = without residue, None = no weed management, Herbicide = atrazine applied and Tillage = simulated tillage (sieving).

As the herbicide was eliminated, the effects of the simulated tillage on the three fertiliser types (No, Min and Org) were pursued through relevant subsets of data. Simulated tillage did not significantly influence TOC for the No fert (P = 0.079) and the Min fert (P = 0.456). However, there was a significant decrease due to simulated tillage in the Org fert ($P < 0.05$) compared to the None (control) treatment as shown in Figure 4.8.

Between the fertiliser types (in ± RES), the Min fert had consistently lower average TOC compared to its No fert (control) counterparts, but the difference was not significant. The Org fert treatment showed general increasing trend when compared to the No fert (control) counterparts, but significant difference occurred in the residue incorporated and tilled (+RES: Tillage) treatment only in the Chromosol only. Most significant differences in TOC occurred between the Min and Org fertilisers due to a combination of increase in Org fert and slight decrease in the Min fert (Figure 4.8). On average, the Org fert treatment was 2.0% and 3.3%

higher TOC than the No fert (control) and Min fert, respectively, across the two soil types. Therefore, the TOC concentrations in the three fertiliser treatments were generally in order: Min fert < No fert ≤ Org fert.

The residue incorporated treatments increased TOC concentrations by 14% in comparison to the treatments without residue, on average. Between soil types, the Vertosol increased TOC concentration by 89% in comparison to the Chromosol, on average. The differences due to residue and soil type are also demonstrated by Figure 4.8.

Simulated tillage significantly reduced the TOC concentration in the residue incorporated treatment (in +RES between None and Tillage for Org fert) in the Chromosol but in the Vertosol the significant reduction occurred in the treatment without residue (in –RES between None and Tillage for Org fert). This difference in the effect of weed management on reduction of the TOC in the residue incorporated treatment in the Chromosol and in without residue treatment in the Vertosol has manifested as weed management × residue × soil type significant interaction.

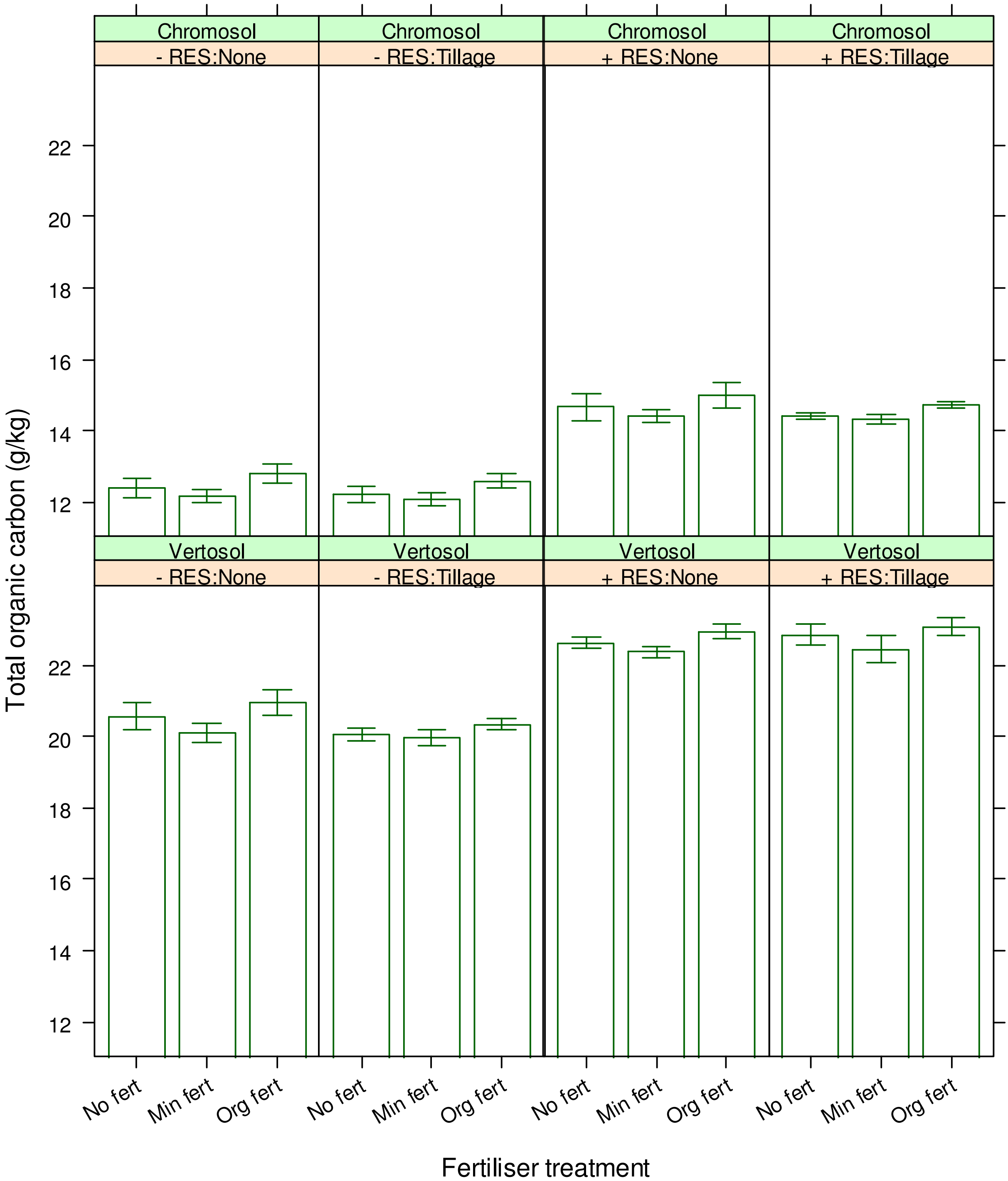


Figure 4.8. Effect of fertiliser and weed managements in with or without residue treatments on total organic carbon. The vertical bars are 95% confidence intervals of means. Note: y-axis does not originate at '0' to demonstrate differences more effectively. No fert = without fertiliser, Min fert = mineral fertiliser, Org fert = organic fertiliser, +RES = residue incorporated, -RES = without residue, None = no weed management and Tillage = simulated tillage (sieving).

4.4 Discussion

4.4.1 Soil pH and EC

Although residue incorporated treatments with higher TOC can increase soil pH (Fuentes *et al.* 2009), our values were not significant. Soil pH increased over time in both soil types because of intermittent rainfall for a prolonged period prior to samplings possibly leaching of soil solutes. The more easily drained Chromosol showed larger increases in pH than the clayey Vertosol where leaching may have been less severe due to better absorption. Although the applications of mineral fertilisers were reported to decrease soil pH compared to organic fertilisers in long-term trials (Birkhofer *et al.* 2008, Heinze *et al.* 2010), we did not find significant differences between the two SMS possibly due to short timeframe or leaching of solutes masking the results.

Electrical conductivity generally decreased for October 2010 and December 2011 samples due to relatively modest fertiliser inputs and to leaching solutes down the soil profile by rainfalls. Residue and SMS were significant because of the release of cations and anions from residue and fertilisers which may have increased the EC (Rayment and Higginson 1992) as residue and N fertiliser are reported to have this effect (Sharma *et al.* 2005, Alijani *et al.* 2012). The higher CEC of the Vertosol would account for larger EC values in that soil type.

4.4.2 TOC and TN

From baseline in December 2009, TOC concentration generally increased over time mainly in the top 0-0.1 m horizon. On average, there was a 7%, 3% and 3% increases in October 2010, March 2011 and December 2011, respectively, from the baseline in the top 0-0.1 m horizon, across the two soil types.

Residue incorporation significantly increased TOC due to the C released from decomposed residue. A recent 2-year study found that incorporation of 25–50% (7.5–15.0 Mg/ha) of chopped corn residues in soil was sufficient to increase TOC in a wheat (*Triticum aestivum* L.)–corn–wheat rotation (Alijani *et al.* 2012). Conversely, after 16 years of experimentation, Hoyle and Murphy (2006) found no difference in TOC between residue retention and burning, however the quantity of residue retained were smaller in that trial.

Soil type and SMS interacted significantly because the response of SMS was detected in SOC-poor Chromosol only and not in SOC-rich Vertosol. The effect of SMS was not significant during December 2011 possibly due to loss of labile C resulting from the longer time interval between organic fertiliser incorporation and sampling compared the other sampling intervals and the easily decomposable C:N ratios (≤ 5.4) of the organic fertilisers. TOC in organic systems is generally reported to be higher than in the conventional systems (Clark *et al.* 1998, Teasdale *et al.* 2007, Heinze *et al.* 2010, Mancinelli *et al.* 2010) but inconsistencies do exist (Fließbach *et al.* 2007, Leifeld *et al.* 2009). Under intensive vegetable systems in particular, Wells *et al*. (2000) found that TOC in organic systems was 75% higher than in conventional management systems after three and a half years of conservation management including no-till and high inputs of compost. Application of compost was reported to increase TOC by 77–178 % from 1999 to 2002 compared to the non-amended soils in another vegetable systems (Rotenberg *et al.* 2005).

The higher level of TOC in the Vertosol compared to the Chromosol could be due to adsorption of more C compounds from decomposed residue on the Vertosol's clay-based organo-mineral complexes that help physicochemical stabilisation of C (Hassink 1997, von Lützow *et al.* 2006). Further, physical stabilisation through microaggregation is also likely in the Vertosol, thus protecting TOC from decomposition (Six *et al.* 2002a, Blanco-Canqui and Lal 2004). The soil types and depth interaction was significant because, with increasing depth, the TOC decreased more slowly in the Chromosol, as most of C input from management and through plant roots would occur in upper horizons of the soils (Baker *et al.* 2007, Blanco-Canqui and Lal 2008).The interaction also depended upon textural properties and pre-existing TOC levels of the two soils. For example, the greater TOC concentration at 0.2-0.3 m segment in the Chromosol compared with the Vertosol could be due to its sandy property facilitating downward movement of TOC through the soil profile; but such movement could have been restricted by adsorption in the upper soil layers in the Vertosol (Hassink 1997, von Lützow *et al.* 2006). Total N concentrations generally followed same trend and similar effect as the TOC, which was evident by their strong, positive correlation ($r^2 \geq 0.92$).

4.4.3 Verification of TOC results of field experiment by laboratory experiment

The results of the field experiment showed that the TOC concentration was significantly influenced by SMS (except December 2011 samples), residue incorporation and soil type, in addition to the depth and sampling time. The results of the laboratory experiment conducted to verify field results reconfirmed the effects of residue incorporation and soil type on the TOC concentration. However, separating the confounding factors of the SMS treatments – i.e. herbicide and mineral fertiliser in the conventional SMS and cultivation and organic fertiliser in the organic SMS – were further pursued to account for the effects of each factor. Data from the laboratory experiment showed that the application of atrazine (< 0.5 kg C/ha) to soil did not influence TOC concentration, which eliminated the possibility of atrazine stimulating or killing soil microbes (Barriuso and Houot 1996, Hang *et al.* 2007), and thus, changing the microbial activity. Mineralisation of atrazine in soils with a history of atrazine use, such as our soils, is reported to be ≥ 50% in less than 28 days in laboratory conditions (Hang *et al.* 2003). A recent review by Krutz *et al.* (2010) concluded that residual weed control in atrazine-adapted soil could be ten times lower than non-adapted soils, suggesting the agronomic benefit of residual atrazine accrued in soil. This is because atrazine-adapted soils develop microbial communities capable of using atrazine as a source of C, N and energy (Barriuso and Houot 1996).

The mineral fertiliser treatment consistently decreased the average TOC concentration but these figures were not significant. Therefore, neither atrazine nor mineral fertiliser influenced TOC in the conventional SMS. However, organic fertiliser showed a generally increasing trend when compared to corresponding No fert controls. A significant difference occurred in the residue incorporated and tilled (+RES: Tillage) treatment in the Chromosol but not in the Vertosol. Importantly, the slight decrease in the mineral fertiliser treatment combined with the slight increase in organic fertiliser made the two fertiliser treatments significantly different to each other. This corroborates the fact that N fertiliser may accelerate mineralisation of SOM (Khan *et al.* 2007, Russell *et al.* 2009) or reduce aggregate stability (Fonte *et al.* 2009) whilst the organic fertiliser may increase TOC through physical addition of C and changes to soil function (Wells *et al.* 2000, Pimentel *et al.* 2005). Therefore, the average TOC concentrations in the three fertiliser treatments were generally in the order: Min fert < No fert ≤ Org fert. If we did not have the No fert (control), we would have erroneously concluded that the Org fert increased TOC concentration based on the relative difference. However, relating this result from the laboratory experiment directly to the field experiment is not straightforward because a part N fertiliser in the field condition would be taken up by plants (ultimately returning organic matter to the soil) and some would be leached down the soil profile (Snyder *et al.* 2009). Further, a major review found a positive relationship between N fertiliser use and SOC storage, but SOC was found to increase only when crop residue was returned to soil (Alvarez 2005), reconfirming the important role of crop residue for C sequestration in soil.

The effect of the simulated tillage on the mineral fertiliser treatment was not significant, but its effect was detectable on the No fert (control). There was clear significant decrease in the Org fert (Tillage) treatments compared to undisturbed the Org fert treatment. The decrease in TOC as a result of simulated tillage in the Org fert (Figure 4.8) could be attributed to the very easily decomposable C:N ratios of the incorporated organic fertilisers (Organic Life Garden Food was 4.6 and New Era High N fertiliser was 5.4). In relating this to field observations, cultivation may be expected to cause a decrease in TOC under organic SMS (in contrast to the expected increase due to direct C inputs), but the decrease may not have been high enough to balance out with the conventional SMS. Again, relating the laboratory observation to field conditions may not be straightforward because in the field condition as fertiliser N cycling may be somewhat different (Khan *et al.* 2007, Russell *et al.* 2009) than under the controlled laboratory conditions. It is evident from the data that the effect of simulated tillage was not significant when TOC concentration in the soils was either too low (no residue treatment in Chromosol) or too high (Vertosol with residue). This is because microbial activity could have been minimal due inadequate labile substrate or might not be able to assimilate or process beyond certain thresholds, respectively (Wang *et al.* 2003).

There was a consistently high significance level for the effect of residue incorporation and soil type on the TOC concentration in both the field and laboratory experiments. This confirms that residue incorporation significantly increases TOC concentrations in the field (Alijani *et al.* 2012). On average, the TOC concentration in the Vertosol was consistently higher than the Chromosol due to physicochemical (Hassink 1997, von Lützow *et al.* 2006) and physical (Six *et al.* 2002a, Blanco-Canqui and Lal 2004) stabilisation of C in the clayey Vertosol. For example, at 0-0.1 m depth the Vertosol had the 94% and 89% higher TOC concentrations than the Chromosol in the field and laboratory experiments, respectively.

4.4.4 Bulk density of fine earth

Accurate determination of bulk density of soil can be difficult due to heterogeneous nature of texture, structure, compaction and gravel content. But it is important to do so because even small errors can translate into large absolute errors in calculating SOC stocks (Sanderman *et al.* 2010, Holmes *et al.* 2011). BD was estimated for the fine earth by correction for mass and volume of gravel (Holmes *et al.* 2011). If this correction for gravel was not performed, the SOC stock in the Chromosol would have been erroneous because it was highly gravelly. The

Vertosol had negligible quantities of gravel and so correction was not needed for estimating SOC stocks. Residue incorporation, if not SMS, was anticipated to decrease BD of fine earth; however, the time frame of four cropping seasons may not have been sufficient to produce the anticipated changes. Due to normal soil compaction with depth, there was general increase in the BD in lower layers. The soil types differed because of basic differences in soil texture and structure. The Chromosol was sandier than the clayey Vertosol.

4.4.5 SOC stock

Evaluation of the SOC stock determined that residue incorporation at about 15 Mg/ha per year (oven-dry equivalent) in soil accumulated an average of 0.96 and 1.22 Mg C/ha for Chromosol and Vertosol, respectively, in the field trial after 2 years. Declining soil C levels due to little or no crop residue inputs in vegetable systems (Jackson *et al.* 2004, Chan *et al.* 2007) could be improved if sweet corn is introduced in annual rotation and its residue incorporated. Our result corroborates the finding of Clark *et al.* (1998) that inclusion or exclusion of corn in a rotation had significant effect on soil C levels.

It should be pointed out that these accumulations cannot be used to calculate the sequestration rates as the equilibria were not yet attained. A conversion from cultivation to pasture in north-western New South Wales was estimated to sequester only 0.06 - 0.15 Mg C/ha/year (Wilson *et al.* 2011) and improved management of cropland compared to conventional management are predicted at 0.2 – 0.3 Mg/ha/year for general Australian condition (Sanderman *et al.* 2010) to a depth of 0.3 m. Recent studies indicate that dryland farmers of north-western NSW may not be able sequester soil carbon in at least the short-to-medium term (< 20 years) due to unfavourable conditions such as high temperature and prolonged dry periods (Young *et al.* 2009, Wilson *et al.* 2011). Given that vegetable production normally relies on irrigated farming methods, there is less likelihood that dry periods will limit SOC accumulation.

A study found no change or decreases in SOC stock after 14 years of experimentation with tillage and stubble management (Heenan *et al.* 1995). A meta-analysis of 67 global long-term agriculture experiments that compared soil C sequestration rates between no-till and conventional tillage practices found that the transition from tillage to no-till practices could continually sequester an average 0.48 Mg C/ha/year over a period of 15-20 years until the SOC levels reach a stable equilibrium (West and Post 2002). Other studies project a range of 0.1 to 1.0 Mg C/ha/year for over a 25-50 year period or until a new steady state achieved if 'recommended management practices' that include conservation agriculture with no-till farming, residue mulching, cover cropping, crop rotations, appropriate use of both organic and inorganic fertilisers and other related land management techniques are employed (Jarecki and Lal 2003, Lal 2010). However, a review of conservation agricultural practices on SOC stock under Australian conditions found inconsistent results (Luo *et al.* 2010b) indicating the impact of edaphic and climatic variability as well as differences in land use and management on SOC (Ogle *et al.* 2005, Sanderman and Baldock 2010, Sanderman *et al.* 2010). While shredding residue was undertaken in our trials, it is unlikely to be a practical option for growers. However, the results highlight the potential for increasing soil C using crop residues.

No significant differences were detected between the organic and conventional SMS as the C input through organic fertiliser seems to have been lost mainly because C:N ratios were within very decomposable range (≤ 5.4). A short time frame of 2 years may not have been sufficient to produce anticipated results. Although Leifeld *et al.* (2009) found no significant difference in SOC stocks between organic and conventional systems in their 27-year experiment, a manure-based and legume-based organic faming system accumulated 0.7 and 0.3 Mg C/ha/year (respectively) higher SOC stocks in a 22-year experiment than their conventional counterparts (Pimentel *et al.* 2005). Further, Clark *et al.* (1998) reported that SOC stocks to 0.15 m depth after 8 years to have increased by 0.5 and 0.3 Mg C/ha/year for organic and low-input crop rotations, respectively, in comparison to conventional systems.

The average SOC for the Chromosol to 0.3 m was 30 Mg/ha, less than half of the 64 Mg/ha stock in the Vertosol. This is because the Vertosol had higher initial TOC concentration and more soil mass to the measured depth of 0.3 m than the Chromosol. The lower SOC stock in the Chromosol was because of its higher sand component, lower mass of fine earth (more gravelly) and lower TOC concentrations. Differences in physicochemical properties of soil types can produce large variations in SOC stocks (Sanderman *et al.* 2010, Cotching 2012). Generally, the SOC stock was highest in the top 0-0.1 m layer as organic matter enters soil on the surface and the stock then decreases with soil depth. Our average values for both soil types are higher than those reported for the Red Chromosol and Black Vertosol in other parts of NSW (Young *et al.* 2005) mainly because our sites receive higher annual rainfall, thus contributing to greater plant biomass production and input to the soils. Rainfall can strongly influence the ability of soil to store C. For example, a semi-arid moderately grazed rangeland, that was a net sink of up to 1.6 Mg C/ha/year during the wetter than average year, was a net source of 0.5 Mg C/ha/year during a year that experienced a growing season drought (Sims and Bradford 2001).

4.4.6 Soil basal respiration and microbial biomass C

Time of sampling and residue incorporation had highly significant influence on the basal respiration of the two soil types sampled from the field trials. There was an increasing trend of soil respiration over time indicating the increasing trend of labile substrate through residue, organic fertiliser and rhizodeposition (Martens 1995, Gonzalez-Quiñones *et al.* 2011). The treatments without residue or organic fertiliser also had an increase over time due the organic matter enrichment through plant roots especially via rhizodeposition (Kätterer *et al.* 2011). The baseline basal respiration in the Chromosol was lower than in the Vertosol, but after the imposition of treatment the Chromosol respired at a higher level than the Vertosol. This could be attributed to the fact that the Chromosol had initial lower SOC level than the Vertosol and due to larger inter-particular pore spaces in Chromosol aiding high oxygen exchange, whilst the fine-texture Vertosol has smaller inter-particular pores restricting the exchange of gas (Schjønning and Rasmussen 2000).

There was a drop in respiration from October 2010 to March 2011 because labile C stocks could have decreased over time as no additional organic matter was added between the two measurements, particularly in the Vertosol. Incorporated residue was a source of labile substrate for the microbes to greatly increase soil respiration. Compost application can increase soil basal respiration by 200% in comparison to mineral fertilisation (Carpenter-Boggs *et al.* 2000) corroborating the fact that supply of labile C is the key driver of basal respiration and that management system is also important in C dynamics. Mancinelli *et al.* (2010) reported that organic systems were releasing more CO_2 than conventional systems when temperature and moisture were optimal in the field.

MBC is a surrogate measure of labile pool of C (Martens 1995) and is recommended as an indicator of soil biological fertility (Gonzalez-Quiñones *et al.* 2011). The data for MBC showed similar general trends as for basal respiration. However, soil type and SMS were also significant unlike for the basal respiration. In the presence of readily utilisable substrate, soil microbes, including dormant ones, may been activated to increase the release of CO_2 (Anderson and Domsch 1978). The microbes in the Vertosol and the organic SMS that remained relatively inactive for basal respiration responded to the addition of glucose, making soil type and SMS significantly different for MBC, indicating higher biological fertility (Gonzalez-Quiñones *et al.* 2011) and higher TOC content (Murphy *et al.* 2011). Our values are within the wide range of 20 to 700 mg C/kg soil reported for Australian agriculture but toward the lower end (van Vliet *et al.* 2000, Pankhurst *et al.* 2003). The Vertosol was higher by 49% in MBC compared with the Chromosol, as the Vertosol had higher TOC concentration. Due to the C input from organic fertilisers, the organic SMS increased MBC by 8% compared with the conventional SMS. Carpenter-Boggs *et al.* (2000) found that soil MBC was about 50% higher in the compost applied treatment compared to the mineral fertiliser treatment in their 2-year study. The MBC or the biological fertility was generally in order: Conv-RES < Org-RES < Conv+RES < Org+RES indicating the increase of labile C in soil (Carter *et al.* 1999, Wang *et al.* 2003). Therefore, incorporation of either residue or organic fertiliser or both can increase the active or biological pool of C, the breakdown of which releases nutrients for plant growth, whether in organic or conventional SMS (O'Donnell *et al.* 2001).

4.5 Conclusion

Total organic C concentration increased consistently with the incorporation of shredded sweet corn residue. However, the effect of SMS was found to be inconsistent especially if measured after 8 months of treatment application. The Vertosol consistently had higher TOC concentration than the Chromosol, across the three soil sampling depths. The results of the laboratory experiment confirmed that the use of atrazine and mineral fertilisers in the conventional SMS in the field experiment could have no significant effect on TOC, whereas both the organic fertilisers and simulated tillage affected the organic SMS scenario significantly, indicating possibility of organic fertilisers in balancing out the loss of C stimulated by cultivation. Under irrigated field conditions, residue incorporation in soil can accumulate an average of 0.48 and 0.61 Mg C/ha/year for Chromosol and Vertosol, respectively. There was positive but weak relation between TOC and MBC across the two soil types. Soil basal respiration and MBC data showed that soil biological fertility can be improved by residue and by combining residue with organic fertiliser. The observed short-term gains have potential to translate into long-term C sequestration if sweet corn is rotated with vegetable crops and residue is incorporated into soil. Moreover, these practices may be an option to counteract the loss of C due to multiple tillage operations that vegetable systems, especially organic ones, routinely use.

Chapter 5. Effect of corn residue incorporation and soil management systems on soil carbon fractions: Results of field and laboratory experiments

Abstract

Vegetable production systems rely on frequent tillage to prepare beds and manage weeds, accelerating losses of soil organic carbon (SOC). Vegetable systems are also characterised by scant crop residue input. Residue incorporation and organic fertilisers could counteract SOC loss due to tillage. We tested this hypothesis in a field trial where the effect of sweet corn (*Zea mays* L. var. *rugosa*) residue incorporation in a corn-cabbage (*Brassica oleracea* L.) rotation using organic and conventional soil management systems (SMS) on soil C fractions was studied over two rotations in two contrasting soil types (Chromosol and Vertosol). We substantiated our field results with a laboratory experiment using residues and simulated tillage. Residue incorporation increased particulate organic C (POC) by 32% in the field experiment and 48% in the laboratory experiment. However, the organic SMS was only significant for dissolved organic carbon. Mineral-associated organic C (MOC) and total organic carbon (TOC) were positively impacted by residue incorporation in the field and laboratory. Simulated tillage had limited impact on POC, MOC and TOC, suggesting that cultivation for weed control in the organic SMS may have only had a minor effect on SOM mineralisation rate in the short-term. MOC was the major pool (~78%) of TOC in both experiments. The short-term gains observed have the potential to translate into long-term C sequestration in soil. In vegetable systems, role of physicochemical stabilisation is more prominent rather than through the aggregation due to its reliance of on tillage.

5.1 Introduction

Soil organic carbon (SOC) determines the physical, chemical and biological properties of soil. Thus, maintaining or improving SOC stocks is fundamental to sustaining crop productivity and mitigating climate change. A concern about declining SOC due to farming and the rise of atmospheric CO_2 concentrations has encouraged adoption of conservation agricultural practices (Johnson *et al.* 2007, Smith *et al.* 2008). The conservation agricultural practices like no-till farming or crop residue retention are expected to sequester carbon in the soil by way of reducing microbial mineralization and by stabilising added C as inputs.

There are different models of carbon stabilisation or protection of soil organic matter (SOM) from mineralisation in soil. The most commonly accepted models are based on the three mechanisms: the physical protection through soil aggregation, the physicochemical protection through binding of C particles on mineral colloids, and the biochemical protection (recalcitrance properties) of organic matter entering the soil (Six *et al.* 2002a, Bronick and Lal 2005, von Lützow *et al.* 2006).

The aggregation model of carbon stabilisation is based on the size of soil aggregates where macroaggregates (> 250 µm) provide minimal physical protection (Elliott 1986, Beare *et al.* 1994) and microaggregates (< 250 µm) including those within macroaggregates provide high physical protection against microbial decomposition (Six *et al.* 1999, Balesdent *et al.* 2000, Blanco-Canqui and Lal 2004) which is determined by the silt plus clay content (< 53 µm) of the soil and the availability of organic matter to form the matrix of an aggregate. The aggregates physically protect SOM from decomposition by forming spatial barriers that reduce accessibility of the soil microorganisms to their enzymes, substrates and oxygen flow (Blanco-Canqui and Lal 2004, von Lützow *et al.* 2006).Thus, confinement of plant debris in the core of microaggregates is the SOC sequestration mechanism through soil aggregation (Six *et al.* 2002a, Blanco-Canqui and Lal 2004).

The physicochemical stabilisation of SOC is due to sorption of SOC particles on silt plus clay surfaces (< 53 µm) or the mineral colloids (Hassink 1997, Christensen 2001, von Lützow *et al.* 2006). The extraction method developed by Cambardella and Elliott (1992) is used popularly to isolate particulate (> 53 µm) and mineral-associated organic carbon fractions (< 53 µm) to assess the extent of the physicochemical stabilisation. The SOC particles bound on the surfaces of organo-mineral colloids are believed to be stabilised because the SOM is older (Eusterhues *et al.* 2003) or has a longer turnover time than other SOM fractions (Balesdent 1996, Ludwig *et al.* 2003). The chemical and physical properties of a mineral matrix as well as the morphology and the chemical structure of SOM determine the extent to which SOC is stabilised on minerals (Baldock and Skjemstad 2000). However, it is not clearly understood as to why there is a reduction of microbial decomposition of the SOC particles bound on mineral surfaces (von Lützow *et al.* 2006).

The biochemical stabilisation of organic matter is based on the intrinsic properties of the plant materials entering the soil, like lignin content which exerts chemical resistance to microbial decomposition (Christensen 2001, von Lützow *et al.* 2006). The materials with such biochemical properties are also associated with a soil matrix that acts against microbial breakdown (Magill and Aber 1998, Bronick and Lal 2005). For example, corn (*Zea mays* L.) residues are high in lignin and phenols content that determine microbial palatability reducing the rate of decomposition (Magill and Aber 1998) whereas vegetables like cabbage (*Brassica oleracea* L.) are low in lignin content and are hence subject to rapid decomposition. A high level of phenolic compounds in corn residues are also precursors of soil aggregation (Martens 2000). Hence, SOC with complex biochemical properties is less prone to microbial breakdown than those with less complex and labile SOC, which easily decomposes.

Awareness on the negative impacts of tillage, such as declining SOC and increasing atmospheric CO_2 (Johnson *et al.* 2007, Smith *et al.* 2008) has led the farming systems to adopt no-till farming in preference to convention tillage (Luo *et al.* 2010b). However, whilst no-till farming is suited for cereals it is not usually suited for vegetable crops that need intensive care, that rely on tillage to perform basic management operations like preparation of beds and management of weeds and insects. These tillage operations disrupt soil aggregates exposing the physically protected SOM leading to loss of soil organic carbon (Angers *et al.* 1993, Six *et al.* 1999, von Lützow *et al.* 2006) which leads to a decline in soil productivity. Carbon input through crop residue incorporation could be one way to balance this loss and avoid SOC decline (Luo *et al.* 2010b) in a system where tillage is essential. Organic vegetable systems rely on tillage for weed control, whereas conventional systems use herbicides to manage weeds (Bond and Grundy 2001, Bàrberi 2006, Chirinda *et al.* 2010). In addition, organic soil management system (SMS) use organic sources (like crop residue and compost) for fertilisation but conventional SMS use mineral fertilisers as the main source of crop nutrition (Mondelaers *et al.* 2009, Chirinda *et al.* 2010). These management differences have a direct impact on the carbon balance of each system.

A management induced changes in soil can be indicated by labile fraction, particulate organic C (POC) that comprises occluded C in aggregates and the unprotected C (Cambardella and Elliott 1992, Chan 1997). Whilst the mineral-associated organic C (MOC) indicates the stable fraction formed by binding of C molecules on silt plus clay minerals, a mechanism that is considered as a means of long term sequestration of C in soil (Hassink 1997, Kögel-Knabner *et al.* 2008). Vegetable systems are vulnerable to rapid declines in SOC as they are characterised by very little crop residue input and heavy reliance on tillage (Jackson *et al.* 2004, Chan *et al.* 2007). We examined our hypothesis that vegetable systems could be made more resistant to the effects of tillage by including a high-residue grain crop of sweet corn

(*Zea mays* L. var. *rugosa*) in the rotation with cabbage through a two-year field trial. The effect of corn residue incorporation in organic and conventional SMS on the POC, MOC fractions, dissolved organic C (DOC) and total soil organic C (TOC) was investigated. Since the type of tillage determines the rate SOC breakdown whilst crop residue management determines the rate of organic C input to a system (Liu *et al.* 2009, van Groenigen *et al.* 2011), the weed management (tillage in organic SMS and herbicide in conventional SMS) and residue incorporation were suspected of exerting opposite influences on SOC (Luo *et al.* 2010b). To substantiate the results from the field trial we conducted a five-month long incubation experiment aimed at determining the effects of these two opposing factors (residue and tillage) on the POC and MOC fractions and the TOC by incorporating corn residues in soil and simulating tillage (sieving).

The objectives were:

1) to investigate the effect of corn residue incorporation in organic and conventional SMSs on POC, MOC, DOC and TOC in a field trial and
2) to further investigate the effect the corn residue incorporation (with or without) and the weed management (with or without simulated tillage) in the laboratory conditions to supplement and/or confirm the field results.

5.2 Materials and methods

5.2.1 Field experiment

A soil management systems field trial was conducted over a 24-month period at two cropping sites in the Armidale area of New South Wales, Australia with two contrasting soil types: a mottled, dystrophic, Brown Chromosol, medium, loamy, non-gravelly (referred to hereafter as Chromosol) and a haplic, self-mulching, Black Vertosol, very fine (referred to hereafter as Vertosol) in the Australian soil classification system (Isbell 2002). These correspond to Alfisol and Vertisol, respectively, in the USDA classification (Soil Survey Staff 2010). Selected soil properties for the two soils are given in Table 5.1. The coordinates for the Chromosol site are 30° 29.23′ S and 151° 38.08′ E at an elevation of 1,011 m and that of Vertosol site are 30° 28.55′ S and 151° 38.93′ E at an elevation of 1,077 m.

Table 5.1. Mean values for selected soil properties for 0-10 cm depth of field trial sites (n = 4).

Soil type	C	N	Sand	Silt	Clay	Ca	K	Mg	Na	BD[a]	pH
			g/100g					$cmol_c/kg$		Mg/m^3	$(H_20)_{1:5}$
Chromosol	1.28	0.13	74.3	10.6	14.5	1.74	0.38	0.65	0.07	1.47	5.6
Vertosol	2.41	0.20	22.4	15.6	62.3	21.71	0.59	12.90	0.18	1.22	5.5

[a] bulk density

Sweet corn (summer) and cabbage (winter) rotation with two SMS (organic or conventional) with two residue management practices (incorporation = +RES or removed = -RES) were used. The experiment commenced in December 2009 and ended in December 2011 completing four cropping seasons. A completely randomized design with two-way factorial levels was adopted and each treatment had four replications. Each plot was 6 m x 2 m in size. Corn was sown using a tractor-mounted seeder and the planting density was maintained at 70,000 plants/ha in four rows spaced 0.5 m apart. Corn was fertilised in organic (Org) and conventional (Conv) SMS at the recommended rate of 200:50:40 kg/ha N:P:K (NSW DPI 2009). Commercially available organic fertilisers (New Era High N® and Organic Life Garden Food®) were applied pre-sowing for Org SMS, and urea, trifos and muriate of potash were used in the Conv SMS. Half of the fertilisers were banded along the four rows and the other half spread evenly over each plot. Half of the N fertiliser in Conv SMS was applied at sowing and the rest as a top dressing one month after sowing. Weeds in Org SMS were managed using a chipping hoe at three and seven weeks after sowing. Weeds in Conv SMS were managed using 2 L/ha Atrazine® (480 g/L of S-triazine as active ingredient) at pre-emergence and three weeks after sowing. No other crop protection was required for corn in both years. The crop was irrigated using drip irrigation. After harvesting cobs, corn stover was shredded mechanically with a mulching machine, spread evenly across the +RES plots at 14.8 t dry weight/ha (estimated average yield) and incorporated using rotary hoe to a depth of 15-20 cm. The stover had the average C:N ratios of 43:1 in 2010 and 53:1 in 2011.

Cabbage seedlings were raised in a greenhouse. At eight weeks, the seedlings were manually transplanted in the +RES or –RES plots at 40,000 plants/ha (four rows per plot). The cabbages were fertilised with 120:65:45 kg/ha N:P:K (NSW DPI 2006) using the same combinations of organic and mineral fertilisers as in the corn. Similar to the in corn, half of the fertilisers were banded along the four rows and the other half spread evenly over each plot. Half the N fertiliser in the Conv SMS was applied as top dressing one month after transplanting. As with the corn, cabbage crops were also irrigated by drip irrigation. Gypsum was applied (330 kg/ha) as the sulphur supplement in mid-June to all plots. Weeds in Conv plots were managed by manually pulling out the weeds with minimum soil disturbance at three and seven weeks after transplanting. Weeds in Org plots were managed using a chipping hoe at three and seven weeks after transplanting. Cabbage moth and cabbage white butterfly caterpillars were controlled using Dipel® (active ingredient = 4320 international units of potency/mg of *Bacillus thuringiensis* var. *kurstaki*) twice in September 2010 with a 15 day interval in all plots, but no insect control was required for the 2011 crop.

In 2011, the corn crop was followed by cabbage in the same sequence, however, the corn crop was planted one month ahead in the season in mid-November 2010 and hence all the other cropping activities for corn and cabbage were brought forward by a month. The soil samples for this section of the research were collected from 0-0.1 m depth two years after initiating the experiment. The samples were dried at 40 °C and sieved through < 2mm sieve to remove > 2mm fractions like crop roots, stones and soil fauna in preparation to fractionate into two carbon fractions. Field moist soil samples were stored at 4 °C for two months before the laboratory determination of DOC in the samples.

5.2.2 Laboratory experiment

We identified residue and weed managements in the field experiment as the two key determinants of soil organic carbon because residue incorporation would increase SOC levels whilst weed management by cultivation would decrease SOC levels (Liu *et al.* 2009). The effects of these two key factors on POC and MOC were investigated further under laboratory conditions. Soils for the laboratory experiment were collected from adjacent plots to field trial locations from each site. The soil samples were air-dried, sieved through < 2-mm sieve, plant debris was removed and finally the soil was homogenised by mixing.

We incorporated ground sweet corn residue (< 4mm) (RES or NoRES) and ± sieved to create soil disturbance (< 4mm) to simulate tillage (+Till or –Till) making four treatment combinations of 'NoRES-Till', 'NoRES+Till', 'RES-Till' and 'RES+Till' in each soil type. The layout was completely randomized with four replications. The NoRES-Till treatment was considered analogous to a conventional SMS as no crop residue usually is applied and weeds are controlled by herbicides. And the RES+Till treatment was considered analogous to an organic SMS as crop residue or organic amendment is applied but cultivation is used as a means to control weeds.

The RES treatments were incorporated with 15 tonnes/ha (7.54g/pot dry weight basis) based on biomass production levels in a related field trial. The C:N ratio of the ground residue was 34:1. The residue incorporation rates were equivalent to 15.08g/kg in Vertosol and 12.57g /kg in Chromosol, due to the difference in bulk density of the two soil types. Five hundred (Vertosol) and 600 (Chromosol) grams of soil (oven-dried basis) were weighed into 8.6 cm diameter polythene pots to a depth of ~0.1 m. Due to different bulk densities, these weights gave similar soil volumes in the pot. The soils were pre-incubated at 25 ºC for four months (mid-January to mid-May 2011) to allow decomposition of the applied residue. During pre-incubation, water was applied once every 14 days for Vertosol and once every six days for Chromosol to raise soil moisture levels from wilting point (-1500 kPa) to field capacity (-33 kPa). The irrigation schedule resulted in 25 and 11 wetting/drying cycles in Chromosol and Vertosol, respectively. Particle size distribution (Table 5.2) of the two soils enabled their hydraulic characteristics to be estimated with the pedotransfer functions of Vervoort *et al.* (2006) for Vertosols and Minasny (2006) for Chromosols.

Table 5.2. Mean values for selected soil properties for 0-10 cm depth used for laboratory experiment (n = 4).

Soil type	C	N	Sand	Silt	Clay	Ca	K	Mg	Na	BD[a]	pH
			g/100g					$cmol_c$/kg		Mg/m^3	$(H_20)1:5$
Chromosol	1.28	0.12	67.9	17.8	14.3	2.42	0.63	0.71	0.03	1.47	6.0
Vertosol	2.47	0.21	24.4	13.9	61.7	26.31	0.72	15.59	0.21	1.22	5.8

[a] bulk density

The aim of sieving was to simulate tillage by disturbing soil in a manner that was analogous to field tilling with a rotary hoe, a common tillage implement used in vegetable production (Kristiansen *et al.* 2008). Soil aggregate sizes after rotary hoeing have been reported to be 40% at ≤ 5 mm and 80% ≤ 15 mm (Braunack and McPhee 1991). At the end of pre-incubation, i.e. when treated soils approached wilting point, they were sieved to disturb soil or simulate tillage (Roberts and Chan 1990, Calderón *et al.* 2000, Kristensen *et al.* 2003) through a 4 mm mesh. This was intended to simulate an intense tillage event (Figure 5.1). . There were two sieving events and the second sieving was performed 15 days after the first. To avoid smearing and for practical convenience, soils were sieved when the soil moisture level dropped close to wilting point. The sieving operation (on a sieve-shaker) and repacking of each sample was completed within 10 and 20 minutes for Chromosol and Vertosol, respectively. The remaining hard clods that could not be broken by sieve-shaker were broken gently by hand or by mortar and pestle. The action of sieving broke up soil into smaller clods, mixed up any crop debris or soil amendment and exposed soil to aeration (Dao 1998, Conant *et al.* 2007). Soil samples were air dried and sieved through < 2 mm sieve before fractionating into POC and MOC.

Before sieving (RES+Till)

Before sieving (NoRES+Till)

Ten days after sieving (RES+Till)

Ten days after sieving (NoRES+Till)

Figure 5.1. Effect of simulated tillage on the soil physical structure of the Vertosol.

5.2.3 Fractionation

The soil samples from the field and laboratory experiments were fractionated following Sanderman *et al.* (2011). The extraction component of this method is based on that of Cambardella and Elliott (1992). Briefly, 10 g of air dry soil (< 2 mm) was weighed out in 50 mL centrifuge tube, filled to 45 mL mark with potassium hexa-meta phosphate solution (5g/L) and tumbled overnight. The duplicate soil samples were used for Vertosol and triplicate for Chromosol based on the estimate of recoveries. The dispersed soil in potassium hexa-meta phosphate solution was fractionated using 50 μm sieve into > 50 μm fraction which consisted of particulate organic matter (POM) plus sand and < 50 μm fraction of mineral-associated organic matter (MOM). An automated wet sieving technique (FRITSCH Vibratory Sieve Shaker Analysette 3 PRO) was implemented for a minimum of three minutes with amplitude of 2.5 mm and time interval of 20 seconds (Sanderman *et al.* 2011). From ≥ 50 µm fraction, POM and sand were separated by flotation. Dry weights of POM and MOM were recovered from water by oven drying at 70 ^{o}C for 72 hours. POC consisted of free organic debris and some larger fragments of organic matter released by the dispersion of soil aggregates. MOC consisted of soil C associated with silt and clay size particles and some smaller fragments of organic matter released by the dispersion of soil aggregates. The two fractions were analysed for carbon and nitrogen to determine concentrations of POC, MOC, nitrogen in POM (POM-N) and nitrogen in MOM (MOM-N).

5.2.4 Dissolved organic carbon

The water-extractable organic C or the dissolved organic C (DOC) was analysed for the soil samples from the field experiment on field moist soil following the procedures of (Chantigny *et al.* (2007) for mineral soils. Briefly, 12 g field moist soil (on dry weight basis) was weighed out in a 50 mL centrifuge tube and 36 mL of 5 milli-molar $CaCl_2$ solution was added and mixed gently by shaking manually for one minute. The tubes were centrifuged for 10 minutes at 12,000 g force and supernatant was filtered through vacuum filter setup equipped with 0.45µm polycarbonate filter paper. The filtrate was analysed with the Total Organic Carbon (TOC) Analyzer (InnovOx Laboratory TOC Analyzer, GE Analytical Instruments, CO 80301 USA) in Non-Purgeable Organic Carbon (NPOC) mode or the DOC mode. The DOC was not determined for the laboratory experiment.

5.2.5 Determination of soil C and N

The two fractions of POM and MOM samples were analysed for soil C concentration in laboratory by dry the combustion method. Approximately 0.3000 g of finely ground (<0.5mm) sample was weighed into tin cups and analysed by a complete combustion method at 950 ^{o}C furnace (TruSpec Carbon and Nitrogen Analyser, LECO Corporation). The soil C concentration of each fraction obtained from LECO was converted to soil C content for an equivalent soil mass basis based on the dry mass of POM and MOM recovered and the dry mass of soil used for fractionation. The TOC was estimated by summation of the POC and MOC values of corresponding samples and similarly total nitrogen (TN) by the summation of POM-N and MOM-N.

5.2.6 Statistical analysis

A three-way analysis of variance (ANOVA) was used to assess the effects of residue incorporation, soil management system and soil type the on the POC, MOC, DOC, TOC, POM-N, MOM-N and TN using R version 2.11 (R Development Core Team 2010) for the data of both field and laboratory experiments. Variances were checked by plotting residual vs. fitted values and the q-q plots to assess the normality assumptions of ANOVA. No transformations were required. *P*-values < 0.05 were considered significant. Significantly different means were separated using 95% confidence intervals (standard error × 1.96) (Brandstätter 1999). A correlation analysis was done to establish the relationship between the any two soil C fractions.

5.3 Results

5.3.1 Field experiment

Particular organic matter

The ANOVA showed that residue incorporation factor was highly significant ($P < 0.001$) on the particulate organic C. However, soil type and SMS did not have a significant effect, nor did any of the interactions (Figure 5.2A). The residue incorporated treatments, on average, had 32% more POC than the unamended treatments across the two soil types.

Similar to the case of the POC, the POM-N was also significantly ($P < 0.01$) impacted by residue incorporation only (Figure 5.2B). The factors did not interact significantly on the POM-N. However, there was a detectable interaction ($P = 0.088$) between residue and soil type. The residue incorporated treatments, on average, had 20% more POM-N than the unamended treatments across the two soil types.

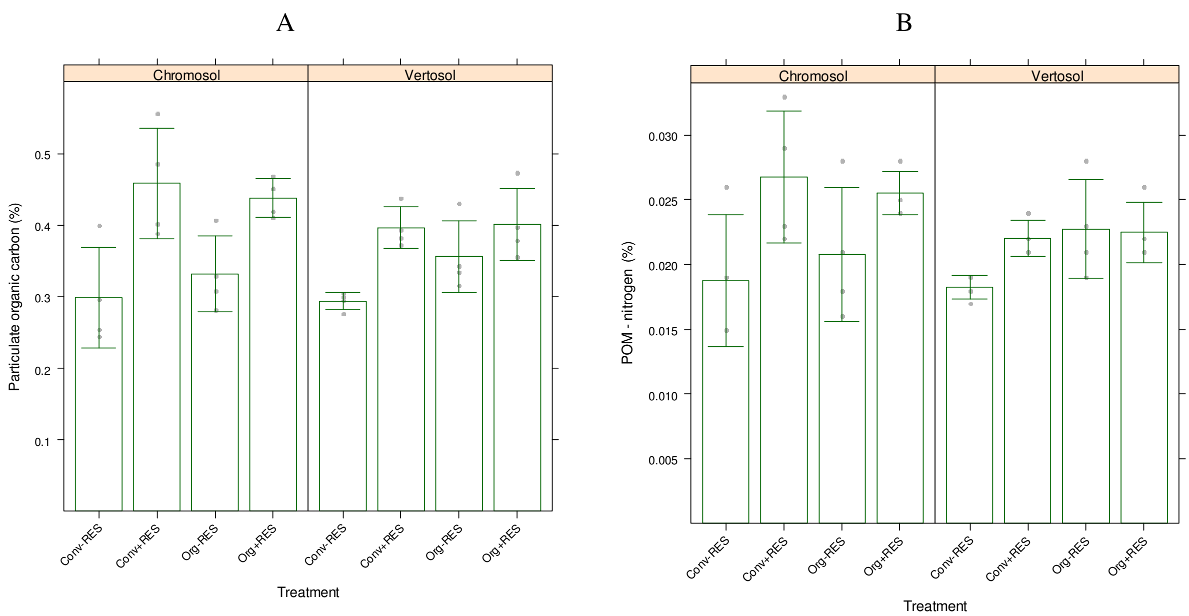


Figure 5.2. The effect of corn residue, soil management systems and soil types on (A) the particulate organic carbon and (B) Particulate organic matter (POM) -nitrogen. Means ± 95% confidence intervals of means (vertical bars) shown. Grey dots are raw data points. Conv±RES = conventional soil management treatments with or without residue incorporation; Org±RES = Organic soil management treatments with or without residue incorporation.

Mineral-associated organic matter

Soil type and residue incorporation had highly significant ($P < 0.001$) effects on the mineral-associated organic C fraction. However, SMS did not have a significant effect, nor did any of the interactions. The Vertosol had 93% more MOC than the Chromosol (Figure 5.3A). Residue incorporated treatments had 5% more MOC in comparison to the unamended treatments.

Soil type was highly significant ($P < 0.001$) for the MOM-N and residue incorporation and SMS were moderately significant ($P < 0.05$) (Figure 5.3B). None of the interactions between the factors were significant. Vertosol had 73% more MOM-N than the Chromosol. Residue incorporation increased MOM-N by 4.5% and the organic SMS had 4.5% more MOM-N than the conventional SMS.

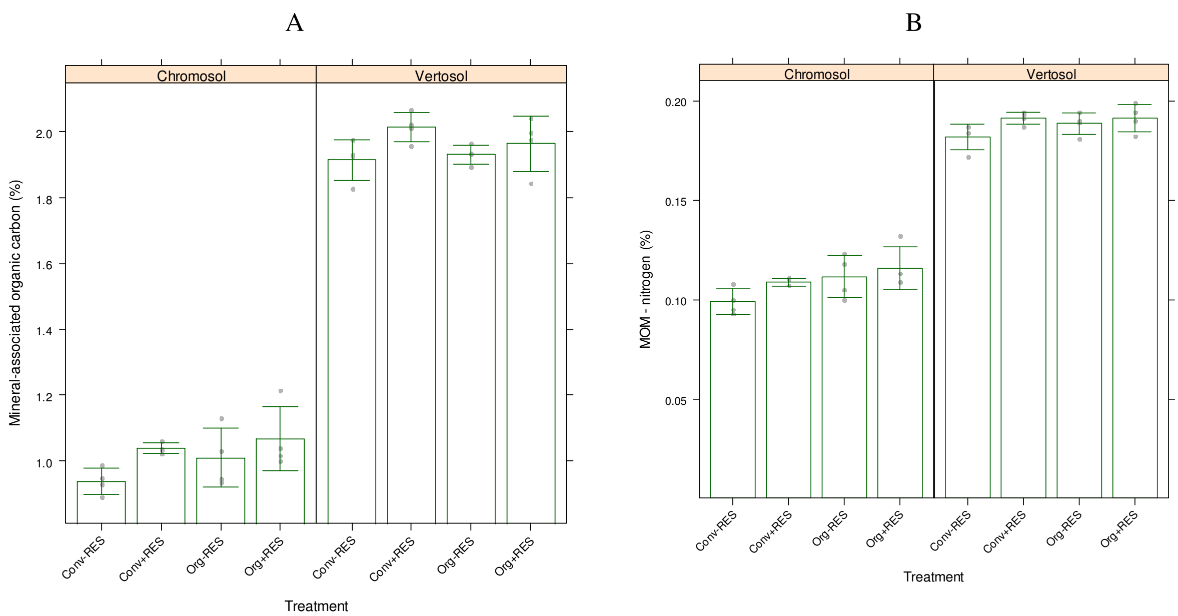


Figure 5.3. The effect of corn residue, soil management systems and soil types on (A) the mineral-associated organic carbon and (B) mineral-associated organic matter (MOM)-nitrogen. Means ± 95% confidence intervals of means (vertical bars) shown. Grey dots are raw data points. Conv±RES = conventional soil management treatments with or without residue incorporation; Org±RES = Organic soil management treatments with or without residue incorporation.

Total organic carbon and total nitrogen

The main factors of soil type and residue incorporation were highly significant ($P < 0.001$) on the TOC, and the SMS was not significant (Figure 5.4A). The factors did not interact significantly. The soil types were significantly different because the Vertosol on average had 66% more TOC concentration than in the Chromosol. The residue incorporated treatments had 10% more TOC in the than the unamended treatments, on average, across two soil types.

In terms of TN, the soil type was highly significant ($P < 0.001$) and residue incorporation and SMS were moderately significant ($P < 0.01$), but no interactions were significant. The Vertosol had 59% more TN than in the Chromosol (Figure 5.4B). The residue incorporation on the average had 6.4% more TN concentration compared with the unamended treatment across two the soil types. The organic SMS had 4.7% more TN than the conventional SMS.

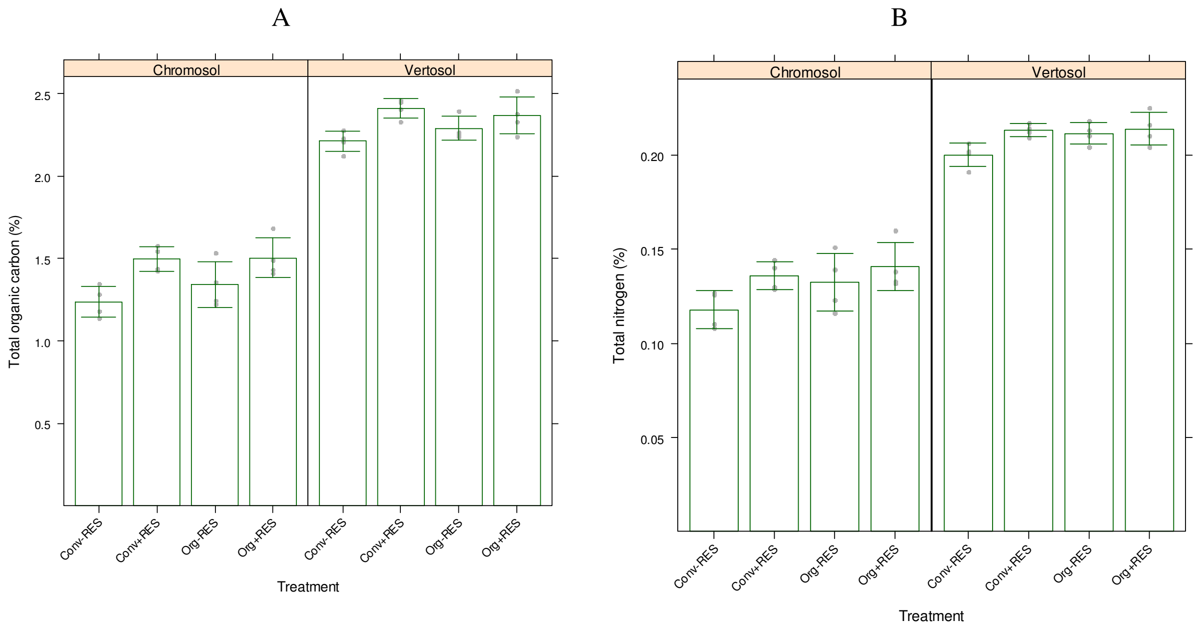


Figure 5.4. The effect of corn residue, soil management systems and soil types on (A) total organic carbon and (B) total nitrogen. Means ± 95% confidence intervals of means (vertical bars) shown. Grey dots are raw data points. Conv±RES = conventional soil management treatments with or without residue incorporation; Org±RES = Organic soil management treatments with or without residue incorporation.

Dissolved organic carbon

The effects of soil type and SMS were moderately significantly ($P < 0.05$) on the DOC and the residue incorporation was highly significant ($P < 0.001$). The effect of soil type was significant due to Vertosol releasing 10% (0.32 µg/g) more DOC than Chromosol, on average. The soil management systems were significantly different due to the organic SMS releasing 11% (0.35 µg/g) more DOC than the conventional SMS on average across the two types. The residue incorporated treatments released 21% (0.67 µg/g) more DOC than the unamended treatments, on average, across the two soil types. The residue incorporation and soil type interacted significantly ($P < 0.05$) for the DOC because residue incorporated treatments in the Vertosol, on average, released 18% (0.63 µg/g) more DOC than the residue incorporated treatments in the Chromosol (Figure 5.5).

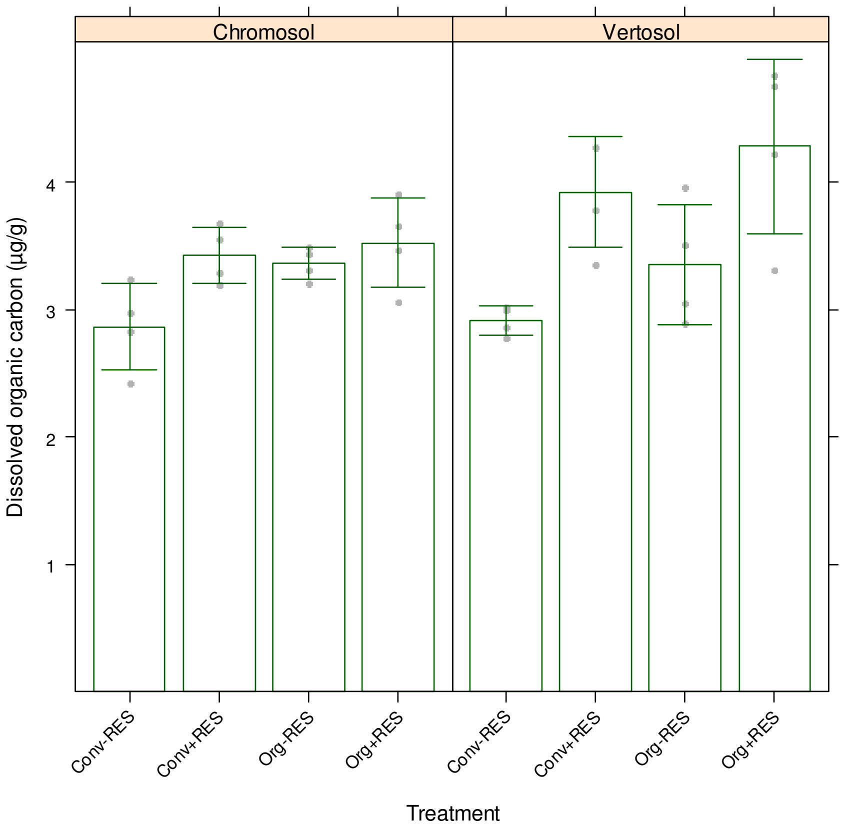


Figure 5.5. The effect of corn residue, soil management systems and soil types on the dissolved organic carbon. Means ± 95% confidence intervals of means (vertical bars) shown. Grey dots are raw data points. Conv±RES = conventional soil management treatments with or without residue incorporation; Org±RES = Organic soil management treatments with or without residue incorporation.

Relationship between the fractions

The correlation analysis showed a positive relationship in any pairs of the POC, MOC, TOC and DOC. As shown in Table 5.3, there was strong positive association between TOC and MOC (r^2 =0.80) followed by POC and TOC (r^2 =0.73) and other pairs were weakly correlated in Vertosol. The correlation coefficients for Chromosol showed strong positive relation between POC and TOC (r^2 =0.84) followed by MOC and TOC (r^2 =0.81) and the other pairs were weakly correlated (Table 5.3).

Table 5.3. Correlation coefficient (r^2) of pairs of soil carbon fractions (n = 16).

	Chromosol					Vertosol			
	POC[a]	MOC[b]	TOC[c]	DOC[d]		POC	MOC	TOC	DOC
POC	1				POC	1			
MOC	0.42	1			MOC	0.28	1		
TOC	0.84	0.81	1		TOC	0.73	0.80	1	
DOC	0.06	0.01	0.03	1	DOC	0.19	0.04	0.13	1

[a] particulate organic carbon (C), [b] mineral-associated organic C, [c] total organic C, [d] dissolved organic C

5.3.2 Laboratory experiment

Particulate organic matter

Soil type and residue incorporation had a significant (*P* < 0.001) impact on POC concentration (Figure 5.6A). However, significant interactions between soil type, residue incorporation and simulated tillage were not present. The clayey Vertosol, on an average, had 16% more POC than the sandy Chromosol. The residue incorporated treatments had significantly higher concentrations of POC in both soil types (Figure 5.6A). On average, residue incorporated treatment had 47% more POC than the unamended treatments across the two soil types.

In terms of POM-nitrogen, only residue incorporation factor was highly significant (*P* < 0.001) (Figure 5.6B). However, neither the other two factors nor the interactions were significant. The residue incorporated treatments, on average, were amounting to 36% more POM-N than the unamended treatments across the two soil types.

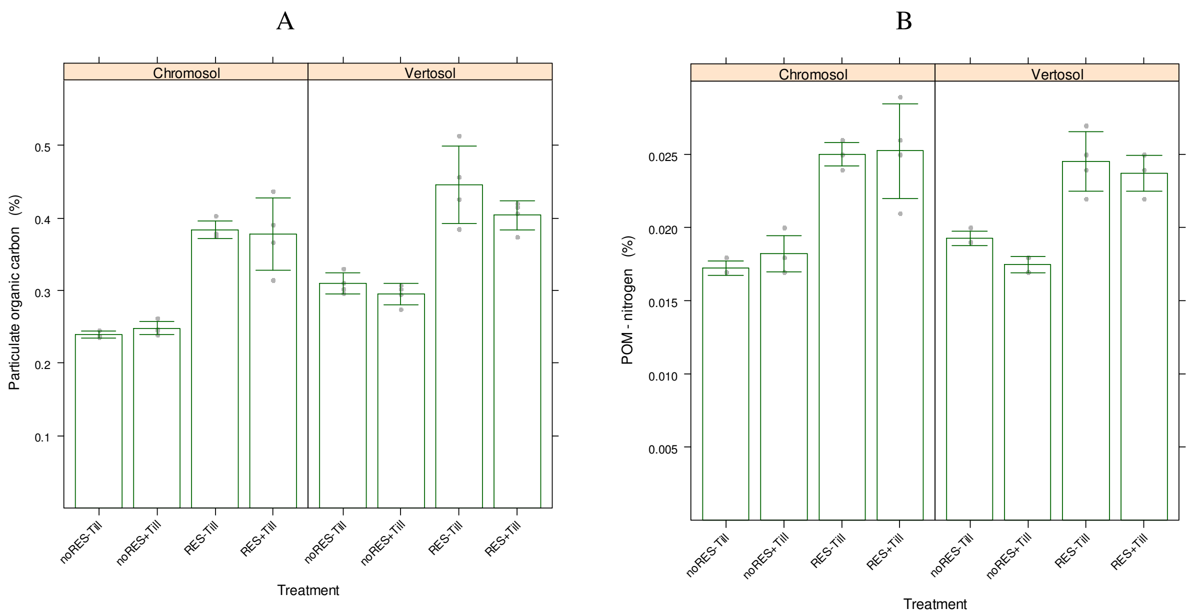


Figure 5.6. The effect of soil types, residue incorporation and simulated tillage on (A) particulate organic carbon and (B) particulate organic matter (POM)-nitrogen. Means ± 95% confidence intervals of means (vertical bars) shown. Grey dots are raw data points. noRES±Till = no residue treatments with or without sieving; RES ± Till = residue incorporated treatments with or without sieving.

Mineral-associated organic matter

Soil type and residue incorporation were both highly significantly (*P* < 0.001) on the mineral-associated organic C and simulated tillage was not significant. The soil types differed because the Vertosol on average had 63% more MOC compared with Chromosol, on average across all treatments (Figure 5.7A). The effect of residue was evident by the fact that the residue incorporated treatments, on average, had 7% more MOC than the unamended treatments across the two soil types. The MOC showed a significant interaction ($P < 0.05$) between residue incorporation and simulated tillage because, the RES+Till treatment had 2% less MOC than the RES-Till treatment and but NoRES-Till had 0.9% more MOC than the NoRES+Till, on average, across the two soil types.

In terms of MOM-N, soil type and the residue incorporation were highly significant ($P < 0.001$) and the simulated tillage was not significant. No significant interactions were found for the MOM-N. The soil types differed because the Vertosol, on average, had 42% more MOM-N than the Chromosol (Figure 5.7B). The residue incorporated treatments had 5% more MOM-N than the unamended treatments, on average, across the two soil types.

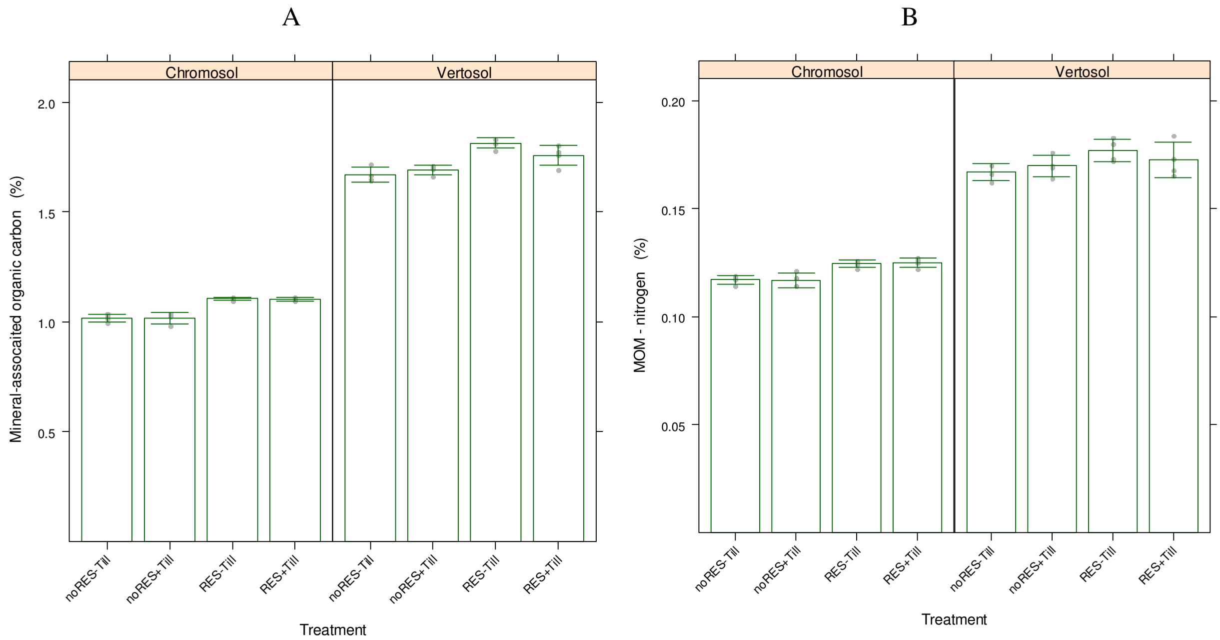


Figure 5.7. The effect of soil types, residue incorporation and simulated tillage on (A) mineral-associated organic carbon (MOC) and (B) mineral-associated organic matter (MOM)-nitrogen. Means ± 95% confidence intervals of means (vertical bars) shown. Grey dots are raw data points. noRES±Till = no residue treatments with or without sieving; RES ± Till = residue incorporated treatments with or without sieving.

Total organic carbon and total nitrogen

Soil type and the residue incorporation were both highly significant ($P < 0.001$) on the TOC. However, simulated tillage did not have a significant effect, nor did any of the interactions. But, a detectable interaction ($P = 0.059$) between residue and simulated tillage was found. The soil types differed because the Vertosol had 53% more TOC than the Chromosol (Figure

5.8A). The residue incorporated treatments had 14% more TOC than the unamended treatments across the two soil types.

The treatment effect on the total nitrogen was similar to that for the TOC, with soil type and the residue incorporation having highly significant (P < 0.001) effect. However, simulated tillage did not have a significant effect, nor did any of the interactions. The soil types differed because the Vertosol had 36% more TN than the Chromosol (Figure 5.8B), on average. The residue incorporated treatments had 8.6% more TN than the unamended treatments, on average, across the two soil types.

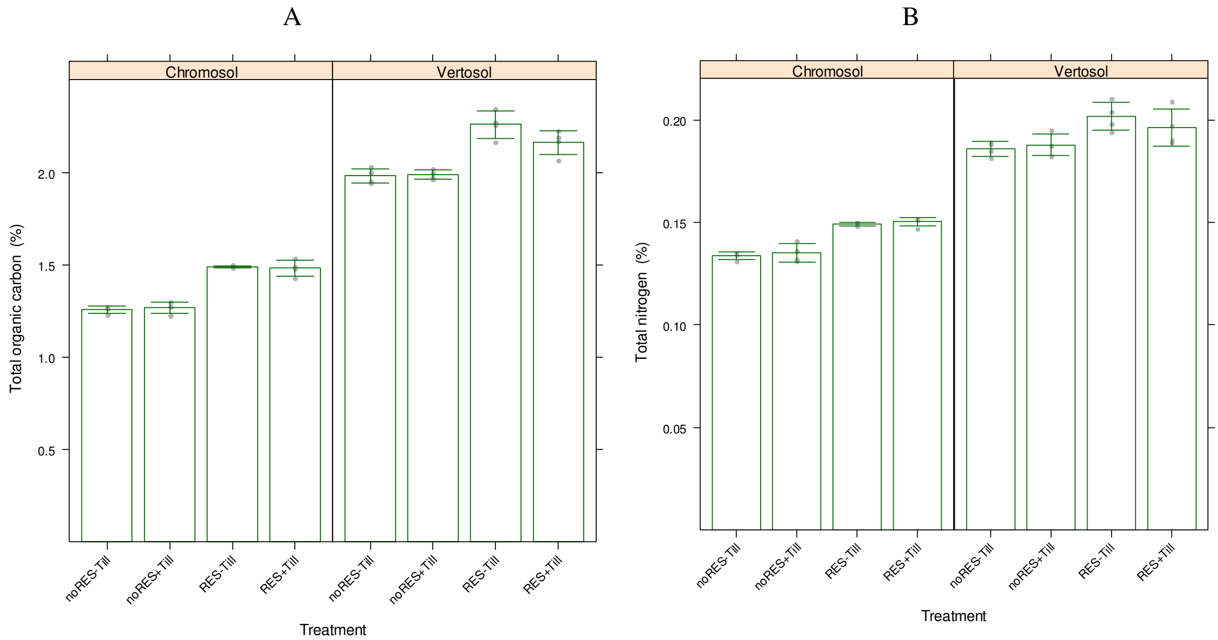


Figure 5.8. The effect of soil types, residue incorporation and simulated tillage on (A) total organic carbon and (B) total nitrogen. Means ± 95% confidence intervals of means (vertical bars) shown. Grey dots are raw data points. noRES±Till = no residue treatments with or without sieving; RES ± Till = residue incorporated treatments with or without sieving.

Relationship between the fractions

The correlation analysis for the laboratory experiment showed the positive relationship between three pairs of POC, MOC and TOC in both the soil types. There was strongest positive association between POC and TOC (r^2 =0.95) followed by MOC and TOC (r^2 =0.94) and by POC and MOC (r^2 =0.78) in Vertosol. The correlation coefficients for Chromosol showed strongest positive relation between POC and TOC (r^2 =0.96) followed by MOC and TOC (r^2 =0.91) and by POC and MOC (r^2 =0.77).

5.4 Discussion

5.4.1 Field experiment

Incorporated residue or organic fertiliser in the soil undergoes a series of processes leading to different pools of unprotected and physically and biochemically protected soil C releasing CO_2 (Six *et al.* 2002a, Blanco-Canqui and Lal 2004). POC consists of mainly the labile fraction which comprises of the occluded C in aggregates and the unprotected C. It can be an indicator of management related changes in soil C due to preferential loss over MOC (Cambardella and Elliott 1992, Chan 1997). The POC fraction in the field experiment was only impacted by residue incorporation due to the labile C input from decomposed residue producing, on average, 32% more POC than unamended treatments across the two soil types. Being biologically active, the POC fraction is more likely to be determined by SMS than by the total SOM (Marriott and Wander 2006a). The effects of SMS on POC were not significant possibly because the C inputs via organic fertilisers may have been negated by the C loss caused by increased mineralisation resulting from soil disturbance (hand hoeing). The increase in POM-N in residue incorporated treatments can be ascribed to the N input from the residue indicating the role of POM-N in increasing soil N (Willson *et al.* 2001).

Dissolved organic C (< 0.45μm) is the most labile and unprotected form of C in soil and represents a small fraction of TOC (Kalbitz *et al.* 2000, Zsolnay 2003). The three main treatment factors individually impacted on the concentration of DOC released. SOC-rich Vertosol released 18% more DOC than SOC-poor Chromosol across all treatments. Increased release of DOC from residue amended treatments was due to the C artefacts originating from decomposed residue. Unlike in the case of the POC, MOC and TOC, the DOC was positively impacted by SMS mainly because the organic SMS (C originating from organic fertilisers) released 11% more DOC than the conventional SMS across the two soil types. Similar to our finding, Marinari *et al.* (2010b) reported significantly higher levels of water-extractable organic C in organically managed treatments compared with conventionally managed treatments at all sites. This is because N from mineral fertlisers accelerate decomposition of residue C and native SOC (Khan *et al.* 2007) thereby reducing soil C. Short term changes in DOC that we have observed are related to soil management practice but the long term changes are driven by vegetation type and by the amount of organic materials entering soil (Chantigny 2003). Filep and Rékási (2011) found that SOM and cation exchange capacity made the maximum contribution to DOC whilst soil N and soil texture exerted a major influence. The organic SMS that relies on organic amendments may result in a net increase of DOC because the mechanical weed management process aids physical and microbial breakdown. DOC is the most mobile form of soil C, so it can easily leach down the soil profile to be stabilised by adsorption on clay mineral surfaces (Kalbitz *et al.* 2000, Chantigny 2003) reducing its decomposition.

Decomposed organic materials follow two pathways for physical protection of C by either binding with the silt plus clay minerals and/or through physical aggregation. Since, soil aggregates were dispersed in the potassium hexa-meta phosphate solution (Cambardella and Elliott 1992), only binding mechanism of C protection was studied. Residue incorporation and soil type had positive significant effect on the MOC fraction. The C input from decomposed residue may have increased adsorption of C molecules on silt plus clay particles as a result of the physicochemical stabilisation mechanism taking place (Hassink 1997, Christensen 2001, von Lützow *et al.* 2006). The different MOC response caused by soil types was due to higher levels of silt plus clay content facilitating more adsorption in the Vertosol than in the Chromosol. The Vertosol also had higher concentrations of pre-experiment C and N than in the Chromosol. The positive significant impact on MOM-N by soil type and residue incorporation can be ascribed to the same process as previously mentioned for the MOC. The organic SMS had on average 4.5% more MOM-N because of the slower mineralisation rate of N in organic fertilisers than in conventional N-fertiliser (urea) (Marinari *et al.* 2010a). Nitrogen from mineral fertilisers promote decomposition of SOM (Khan *et al.* 2007) thereby reducing soil C.

The TOC was positively impacted by soil type due to greater concentration of MOC in Vertosol and by residue incorporation due to the C input from decomposed residue. The TOC was mainly influenced by quantity of MOC which is evident by the strong positive correlation between MOC and TOC. Accordingly, the MOC pool accounted for 84% and 73% of the TOC, on average, for Vertosol and Chromosol, respectively. The soil erosion studies conducted by Boix-Fayos *et al.* (2009) and Martínez-Mena *et al.* (2012) reported that MOC accounted for ≥ 67% of TOC in different land uses, consistent with our finding. Therefore, MOC is the main pool of C in the soil facilitated by the adsorption of C molecules from decomposing residue on the mineral colloids (Christensen 2001, von Lützow *et al.* 2006). The POC pool accounted for 16% and 27% of the TOC, on average, for Vertosol and Chromosol, respectively, mainly due to increase the occluded C in aggregates and the unprotected labile pool, which is sensitive to recent management. The effect of residue on the TOC may also be, to some extent, ascribed to biochemical stabilisation because corn residue is characterised by recalcitrant compounds such as lignin and phenol (Magill and Aber 1998, Martens 2000).

We managed weeds in our organic SMS by hand hoeing, and so the effect of addition organic fertiliser may have been negated by loss of C due to soil disturbance by increased mineralisation of added fertiliser C and the native SOM. Alternatively, the management differences over four cropping seasons might not have been sufficient in time and intensity to produce detectable changes. Therefore, TOC content in the soil is the result of balance between supply of organic inputs and the rate of mineralisation of existing TOC in soil (Stockdale *et al.* 2002). A result of a 27-year experiment on SOC dynamics reported that the loss of SOC was at the expense of MOC whereas the gain was more due to increased the labile fractions and the overall decrease was attributed to reduction of C inputs (Leifeld *et al.* 2009). A recent study re-emphasises the importance of organic C inputs to maintain or increase SOC level in organic farming (Bell *et al.* 2012). The study by Chan *et al.* (2002) indicated that tillage removed mainly POC which accounted for 80% of the total soil C loss but the stubble burning mainly resulted in the loss of MOC. Weeds in the conventional SMS were managed by spraying of herbicide in case of corn or by hand weeding in case of cabbage with minimal soil disturbance to reduce mineralisation of C.

Total N was influenced by the three main factors individually, in the same manner as the MOM-N. The influence of soil type and residue incorporation can be ascribed to the adsorption mechanism (Christensen 2001, von Lützow *et al.* 2006) and higher levels of silt plus clay content in Vertosol. Physical stabilisation through microaggregation is also likely in the Vertosol, thus ‘protecting’ or ‘entrapping’ SOC from decomposition (Six *et al.* 2002a, Blanco-Canqui and Lal 2004). The organic SMS had on average 4.7% more TN because the N in organic fertilisers is mineralised more slowly than that in conventional N-fertiliser (Khan *et al.* 2007, Marinari *et al.* 2010a). The higher concentration of N in the organic SMS may be an advantage for the succeeding crop unlike in conventional SMS where part of fertiliser N is either lost through volatilisation or leaching (Khan *et al.* 2007, Snyder *et al.* 2009).

5.4.2 Laboratory experiment

For the laboratory experiment, incorporating crop residues increased POC concentrations across the two soil types due to C input from the decomposed residue. POC is sensitive to recent management (e.g. residue incorporation) of soil (Cambardella and Elliott 1992, Chan

1997). Thus, residue incorporation accounted for the average of 47% more POC compared with the unamended treatments across the two soil types. Being biologically active, a major part of the POC would be lost within few months due to microbial action. As in the case of field experiment, the SOC-rich Vertosol had higher (16% more) concentrations of POC than the SOC-poor Chromosol due to pre-experiment differences in soil C concentration. There was strong positive association between POC and TOC; POC accounted for 23% and 17% of TOC in the Chromosol and the Vertosol, respectively. The POM-N concentrations, however, were impacted only by residue incorporation as it was closely related to POC concentrations.

Soil type and residue incorporation had impacted MOC concentrations. Owing to the higher silt plus clay content, the Vertosol had 63% more MOC compared with Chromosol, on average. This increase may be facilitated by the physical adsorption of C molecules on the surfaces of organo-mineral colloids (Christensen 2001, von Lützow *et al.* 2006) stabilising the soil C from mineralisation. The two-way interaction of residue and simulated tillage on MOC was because the loss of MOC due to soil disturbance in the presence of incorporated residue was at higher rate than the absence of residue. In other words, increased aeration stimulates more microbes in presence of substrate (residue) than without residue.

Similar to MOC, the MOM-N was also impacted by both the residue incorporation and soil type because of the different pre-experiment N concentrations between soil types and due to N originating from decomposed residue. The correlation analysis showed that TOC was strongly associated with MOC. Accordingly, MOC on average accounted for 83% and 77% of TOC, for Vertosol and Chromosol, respectively, across all treatments. In agreement with our finding, the MOC was the main pool contributing ≥ 67% of TOC in field studies (Boix-Fayos *et al.* 2009, Martínez-Mena *et al.* 2012). The high-activity clay minerals like smectites in Vertisols provide better sorption for C molecules than the low-activity clay minerals such as kaolinite in the Alfisols (Bronick and Lal 2005). Physical protection through microaggregation is also likely in the Vertosol, thus protecting SOC from decomposition (Six *et al.* 2002a, Blanco-Canqui and Lal 2004). Like for the MOM-N, the TN also was impacted by soil type and residue incorporation. The limited effect of simulated tillage on POC and MOC fractions or on the TOC was possibly due to the low intensity (<4 mm sieve) and frequency (twice only) of sieving. In agreement with our findings, Calderón *et al.* (2000) and Kristensen *et al.* (2003) have reported the potentially limited effect of simulated tillage on mineralisation of soil C and N. Under field conditions, no significant differences between tilled and no-till (in five years period) were also reported in a meta-analysis of 69 paired sites experiments in terms of SOC (Luo *et al.* 2010a). Blanco-Canqui and Lal (2008) reported that there was no consistency between no-till and plough-till in terms of SOC in the United States due to variations such as different C distribution patterns through soil profiles manifesting as different, but inconsistent C losses and gains at different depths.

As in the field experiment, only the residue incorporation factor increased POC fraction significantly in the laboratory experiment re-confirming the contribution of residue derived C to the POC. The POC concentration increases in the field and laboratory experiments were 32% and 47%, respectively. Residue incorporation and soil type factors in both the experiments impacted the MOC fraction significantly, and the MOC was found to be the major pool of TOC (Boix-Fayos *et al.* 2009, Martínez-Mena *et al.* 2012) in both experiments, i.e. ≥ 83% in the Vertosol and ≥ 73% in the Chromosol. This phenomenon is the result of association of C molecules on silt plus clay particles which is considered as the main way of long term sequestration of C in soil (Hassink 1997, Kögel-Knabner *et al.* 2008). The short-term gains observed in these experiments have the potentials to translate into long-term C sequestration in soil particularly due to contribution of MOC, if not POC.

The cultivation by hand hoe to control weeds in organic SMS in the field was tested in the laboratory using simulated tillage, whose effect on soil C fractions was not significant. Further, the total organic C in the field and laboratory experiments were impacted by residue incorporation and soil type alike. In vegetable systems, the role of physicochemical stabilisation of soil C is more prominent than aggregation due to the reliance on tillage. Residue incorporation increased TOC by ≥ 10% and the Vertosol by ≥ 53% in both experiments. Therefore, the results of residue decomposition dynamics (Six *et al.* 2002a, Blanco-Canqui and Lal 2004) in the laboratory experiment reconfirm the results obtained from the field experiment.

5.5 Conclusion

The key determinants of soil C fractions were the residue and the soil type in both experiments. Residue incorporation in soil can increase DOC, POC and MOC fractions and TOC in both organic and conventional SMS in the short term. These short-term gains have the potential to translate into long-term C sequestration in soil, particularly due to contribution of MOC, if not POC. The fine-textured Vertosol was more effective in the physicochemical stabilisation of soil C than the sandy Chromosol. Differences due to SMS were limited to the

DOC fraction only making organic SMS better than conventional one. Simulated tillage had limited impact on POC, MOC and TOC highlighting that the hand hoeing operations (cultivation) to control weeds in organic SMS in the field may have limited effect on the rate of mineralisation of SOM in the short-term. The data demonstrated that the MOC was the major pool of TOC in both experiments. In vegetable systems, the role of physicochemical stabilisation of soil C is more prominent than the aggregation due to its reliance on tillage. The POC and TOC were strongly correlated but DOC had a very weak correlation with other three fractions.

Chapter 6. Soil carbon changes and CO_2 emissions due to incorporating corn residues and simulating tillage – A laboratory study

Abstract

Reliance on frequent and intensive tillage by annual horticultural systems to prepare beds and manage weeds and insects reduces soil organic carbon (SOC) through accelerated CO_2 emission. Crop residue incorporation could be one way to counteract this loss. We investigated our hypothesis that vegetable systems could be made more resilient by including a high-residue grain crop like sweet corn (*Zea mays* L. var. *rugosa*) in the rotation through use of conventional (no residue, no sieving) and organic (residue incorporated and sieved) soil management scenarios. We evaluated the short-term emission of CO_2-C and soil C in incubated Chromosol and Vertosol soils with (RES) and without the incorporation of ground sweet corn residue (NoRES), and with (+Till) or without simulated tillage by sieving (-Till). RES emitted 2.3 times more CO_2-C in comparison to -RES, and +Till emitted 1.5 times more CO_2-C than -Till across the two soil types. Residue incorporation had a larger effect on CO_2-C flux than simulated tillage, suggesting that C availability and form can be more important than physical disturbance in cropping soils. The organic scenario (RES+Till) emitted more CO_2, but had 13% more SOC compared with the conventional scenario (NoRES-Till) confirming that organic systems may retain more soil C than a conventional system. The C lost by soil disturbance was more than compensated by incorporation of residue. Relative change in soil may be a better indicator of soil C balance than a snapshot of soil C or total CO_2-C emission.

6.1 Introduction

Annual horticultural systems commonly rely on frequent and intensive tillage to prepare beds and manage weeds and insects. However, tillage stimulates the loss of soil organic carbon (SOC) through accelerated CO_2 emission brought about by improvement in soil aeration and soil and crop residue contact (Angers *et al.* 1993) and disruption of soil aggregates, thus exposing physically protected soil organic matter (SOM) to microbial decomposition (Six *et al.* 2000a, Mikha and Rice 2004). In contrast, some vegetable farmers use green manures, organic inputs (e.g. compost, mulch) and crop residues to perform various functions including increasing SOM. Crop residue management systems that maintain organic materials *in situ* can benefit SOM (Liu *et al.* 2009) and could, in long term, offset the increasing concentration of atmospheric CO_2 by stabilising more carbon in soil (Blanco-Canqui and Lal 2004). Due to the factors outlined above, the effects of tillage and crop residue management can have opposing influences on SOC (Liu *et al.* 2009) and may be difficult to isolate. The type of tillage determines the rate SOC breakdown whilst crop residue management determines the rate organic carbon input to a system (Liu *et al.* 2009). For practical assessment, quantification of effect of each of the two practices individually is desirable to enable evaluation of their contributions separately (Liu *et al.* 2009). Luo *et al* (2010b) summarised the data from 39 published papers for Australian conditions on the interaction of stubble retention and/or conservation tillage on soil C change in the surface 0.1 m of soil. They reported that the synergetic effect of combining stubble retention and conservation tillage increased SOC content by 16% as compared with stubble burning and conventional tillage. Vegetable systems in particular are vulnerable to rapid declines in SOC as they are characterised by very little crop residue input and heavy reliance on tillage (Jackson *et al.* 2004). The SOC pool in the soil is, thus, the balance of C inputs in the form of crop residue and biomass, and C outputs such as CO_2 emissions and other losses.

We hypothesised that such systems could be made more resilient by including a high-residue grain crop like sweet corn (*Zea mays* L. var. *rugosa*) in the rotation. The subsequent corn residue input in the soil could balance the expected loss of SOC due to tillage. This laboratory study was conducted to separate the effects of residue incorporation and tillage in an associated field trial where sweet corn residue incorporation in a corn-cabbage (*Brassica oleracea* L.) rotation had a positive effect on SOC, but no differences in SOC for organic and conventional soil management systems (SMS) (Bajgai *et al.* 2011). Furthermore, organic vegetable systems rely on tillage for weed control, whereas conventional systems rely on herbicide. Also a conventional SMS uses mineral fertiliser as main source of crop nutrition but organic SMS uses organic source (like crop residue and manure) of fertilization in terms C balance in the system (Mondelaers *et al.* 2009). The literature on the interaction of crop residue and tillage on CO_2 flux is scant and often inconclusive due to diverse spatial variations of soil parameters in field conditions.

The laboratory study reported in this paper sought to evaluate the balance of CO_2-C emissions and soil C in incubated soils with and without the incorporation of ground corn residue, and with or without sieving/simulated tillage (mechanical weed control in organic SMS). The objectives were to determine the effect of corn residue incorporation and simulated tillage on 1) the emission of CO_2-C,

2) soil organic C levels, and

3) relative changes in soil organic C over time.

6.2 Methods

6.2.1 Soil selection and experimental design

Soils from 0-0.1 m depth were collected from adjacent plots to both field experiment locations (Chapters 3-5), i.e. two cropping sites in the Armidale area (30° 29′ S, 151° 38 E, 1050 m elevation), New South Wales, Australia: a medium loamy, Brown Chromosol (referred to as Chromosol), and a heavy clay Black Vertosol (referred to as Vertosol) (Isbell 2002). These correspond to Alfisol and Vertisol, respectively, in the USDA classification (Soil Survey Staff 2010). Selected soil properties for the two soils are given in Table 6.1. Soil samples were air-dried, sieved (< 2 mm), plant debris removed and the soil was homogenised by mixing.

Table 6.1. Mean values for selected soil properties for 0-10 cm depth (n = 4).

Soil type	C	N	Sand	Silt	Clay	Ca	K	Mg	Na	BD	pH
			g/100					$cmol_c/kg$		Mg/m^3	$(H_20)_{1:5}$
Chromosol	1.28	0.12	67.9	17.8	14.3	2.42	0.63	0.71	0.03	1.47	6.0
Vertosol	2.47	0.21	24.4	13.9	61.7	26.31	0.72	15.59	0.21	1.22	5.8

Notes: $cmol_c/kg$ = centimole charge per kg, BD = bulk density.

The treatments consisted of two contrasting soils (Chromosol or Vertosol) ± sweet corn residue incorporated (RES or NoRES) and simulated tillage after soils approached wilting point (+Till or –Till). Four treatment combinations were used, 'NoRES-Till', 'NoRES+Till', 'RES-Till' and 'RES+Till', with four replications in a completely randomised layout. The noRES-Till treatment was considered analogous to a conventional SMS as no crop residue usually is applied and weeds are controlled by herbicides. The RES+Till treatment was considered analogous to an organic SMS as crop residue or organic amendment is applied but cultivation is used as a means to control weeds.

The sweet corn residue was ground to < 4mm and incorporated at 15 tonnes/ha based on biomass production levels in a related field trial (Bajgai *et al.* 2011). The C:N ratio of the ground residue was 34:1 (42.1% and 1.25% respectively). The residue incorporation rates were equivalent to 15 g/kg in Vertosol and 13 g/kg in Chromosol, due to the difference in bulk density of the two soil types.

Soil was weighed (500g Vertosol, 600 g Chromosol) into 8.6 cm diameter pots to a depth of ~0.1 m. Due to different bulk densities, these weights gave similar soil volumes in the pot. The soils were pre-incubated at 25ºC for four months (mid-January to mid-May 2011) to allow decomposition of the applied residue. During pre-incubation, water was applied once every two weeks for Vertosol and once every six days for Chromosol to raise soil moisture levels from wilting point (-1500 kPa) to field capacity (-33 kPa). The irrigation schedule resulted in 25 and 11 wetting/drying cycles in Chromosol and Vertosol, respectively. Particle size distribution (Table 6.1) of the two soils enabled their hydraulic characteristics to be estimated with the pedotransfer functions of Vervoort *et al.* (2006) for Vertosols and Minasny (2006) for Chromosols.

The aim of sieving was to simulate tillage by disturbing soil in a manner that was analogous to field tilling with a rotary hoe, a common tillage implement used in vegetable production (Kristiansen *et al.* 2008). Soil aggregate sizes after rotary hoeing have been reported to be 40% at ≤ 5 mm and 80% ≤ 15 mm (Braunack and McPhee 1991). At the end of pre-incubation, i.e. when treated soils approached wilting point, they were sieved to disturb soil or simulate tillage (Roberts and Chan 1990, Calderón *et al.* 2000, Kristensen *et al.* 2003) through a 4 mm mesh. This was intended to simulate an intense tillage event. There were two sieving events and the second sieving was performed 15 days after the first. To avoid smearing, soils were sieved when the soil moisture level dropped close to wilting point. The sieving operation (on a sieve-shaker) and repacking of each sample was completed within 10 and 20 minutes for Chromosol and Vertosol, respectively. The remaining hard clods that could not be broken by sieve-shaker were broken gently by hand or by mortar and pestle. The action of sieving broke up soil into smaller clods, mixed up any crop debris or soil amendment and exposed soil to aeration (Dao 1998, Conant *et al.* 2007).

6.2.2 Gas sampling and analysis

After imposing the simulated tillage treatments, pots were watered to field capacity before placing the pots in plates with 300 ml water. The pots were sealed by inverted plastic tubes over the pots in the plate with water to facilitate gas sampling (Figure 6.1). The effective headspace volume for air sampling was 1.01 litres. The air samples were drawn through a rubber septum inserted on the cover using a surgical needle mounted on a syringe. The air samples were taken before covering and 30 minutes after covering, and the difference in concentrations was calculated as the flux of CO_2. Air samples were collected 24 hours (h) before the first simulated tillage, and 1 h, 120 h, 240 h and 360 h after the first simulated tillage. Gas sampling schedule was amended for second simulated tillage to capture activity between 1 h and 120 h and so sampled 24 h before the second simulated tillage, and 1 h, 4 h, 8 h, 24 h 48 h, 168 h after the second simulated tillage. The air samples were stored in evacuated vials (Labco Exetainer®) and analysed with a gas chromatograph (GC450 with CombiPal autosampler, Agilent Technologies Varian Australia Pty, Australia).

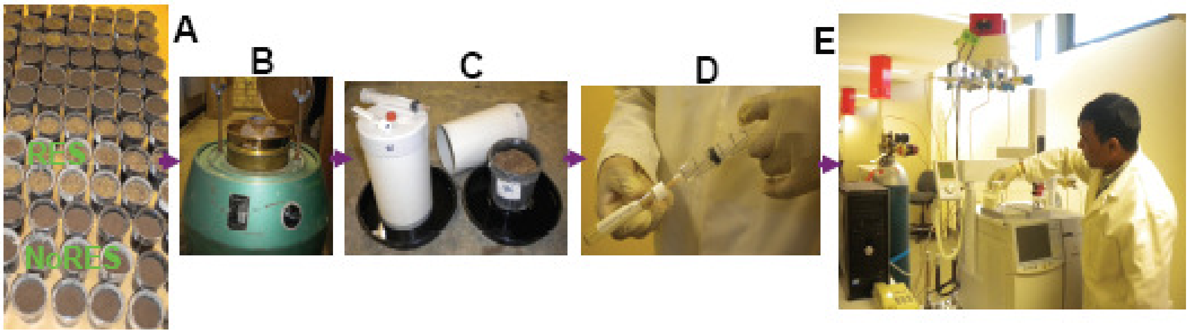


Figure 6.1. Summary of the methodology: (A) treatments prepared, (B) < 4 mm sieve mounted on sieve-shaker to simulate tillage, (C) sealed chamber used for headspace gas sampling, (D) samples in evacuated vials and (E) sample analysis by gas chromatograph.

After gas sample collection, soils were air dried, sieved (< 2 mm), ground (< 0.5 mm) and analysed for total organic carbon (TOC) and total nitrogen (TN) by a complete combustion method at 950°C furnace (TruSpec Carbon and Nitrogen Analyser, LECO Corporation) for C and N concentrations. The total organic C in the beginning (TOC_a) of experiment was calculated by summation of C in each soil (using LECO) and that from the residue incorporated. The TOC at the end (TOC_b) was derived from the LECO results of samples at the end of five months. The relative change in soil C for each pot was calculated using the formula $TOC_\Delta = (TOC_b - TOC_a) / TOC_a$ to effectively compare between the treatments.

6.2.3 Statistical analysis

A three-way analysis of variance (ANOVA) was used to assess the effects of soil type, residue and simulated tillage on CO_2-C flux, TOC, TN and C:N ratio using the R (version 2.11). The data were square root or log transformed to stabilise variances when data deviated from the normality assumptions. Significantly different means ($P \leq 0.05$) were separated using confidence intervals (standard error × 1.96) (Brandstätter 1999).

6.3 Results

6.3.1 CO_2-C flux for first simulated tillage

The CO_2-C flux for all treatments at -24 h (24 hours before simulated tillage) was consistent due to lack of soil moisture (Figure 6.2). However, after simulated tillage and water was applied, large increases were observed at 1 h to ~ 77 mg/m^2/h on average, followed by a decline to pre-tillage levels (slightly higher in Chromosol) at 120 h, 240 h and 360 h.

The interaction between residue and simulated tillage was not significant at any time for Vertosol. But the Chromosol showed significant interactions at 120 h after simulated tillage due to lack of tillage effect in NoRES+Till (7 CO_2-C mg/m^2/h), but RES+Till treatment resulting in the synergy between residue and tillage to release the highest amount of CO_2-C, 61% more than RES-Till treatment, particularly in the first 1 h. The main effect of simulated tillage was not significant at all sampling times. In the SOC-poor Chromosol, the impact of residue was more significant compared to the SOC-rich Vertosol.

Differences in total CO_2-C evolved were significant for residue incorporation and simulated tillage but not soil type. All interaction terms were not significant, but RES emitted 2.6 times more CO_2-C compared to NoRES and the +Till treatments emitted 1.5 times more CO_2-C than -Till.

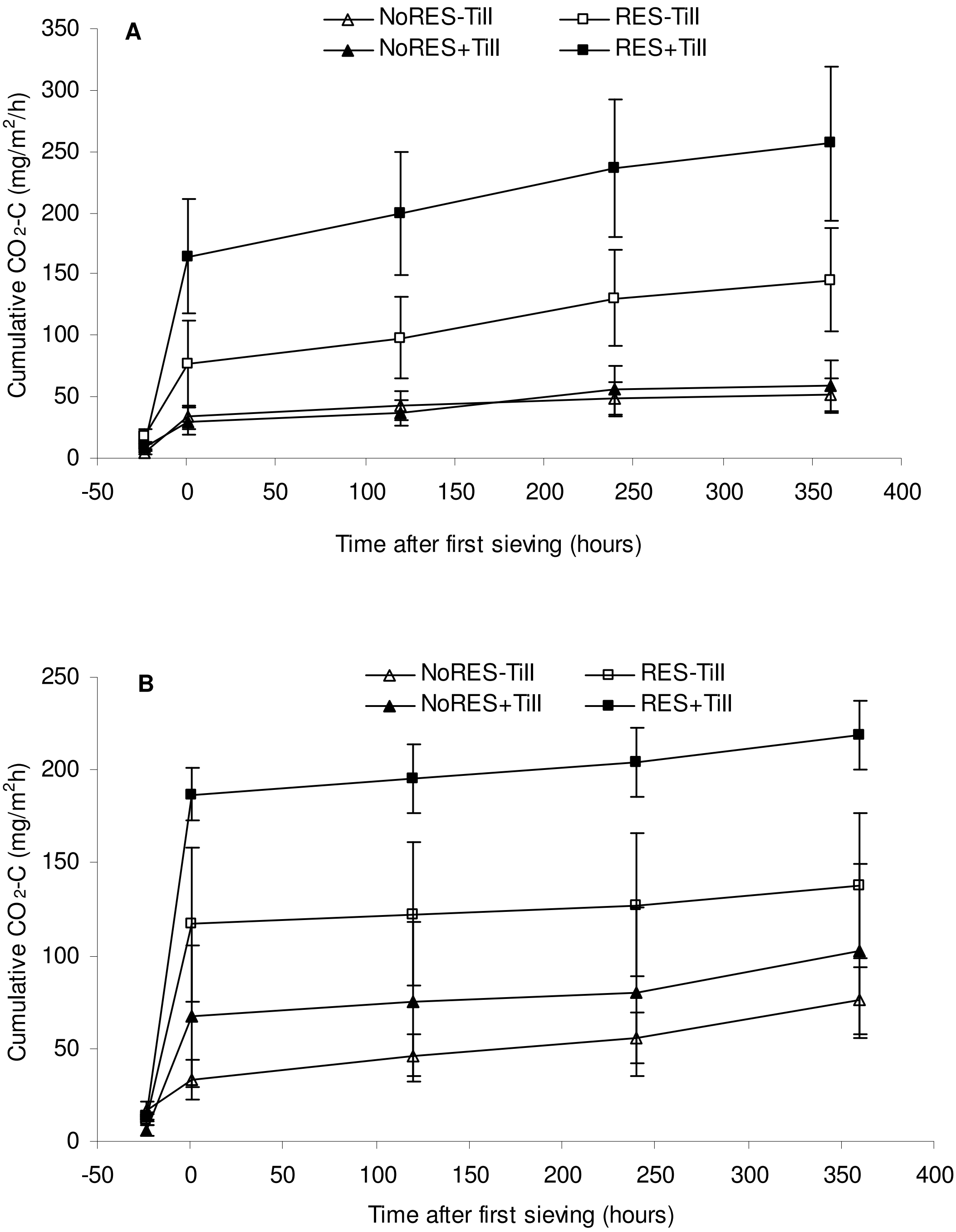


Figure 6.2. Cumulative CO_2-C flux for the first simulated tillage. Means ± standard errors (vertical bars) are presented. A = Chromosol; B = Vertosol; NoRES-Till = without residue and unsieved; NoRES+Till = without residue and sieved; RES-Till = residue incorporated and unsieved; RES+Till = residue incorporated and sieved.

6.3.2 CO_2-C flux for second simulated tillage

The cumulative CO_2-C flux for all treatments at -24 h for the second simulated tillage event responded in a same way due to lack of soil moisture (Figure 6.3). Unlike in the first simulated tillage event, no interactions between residue and simulated tillage were significant for the Chromosol, but the interactions between simulated tillage and residue in Vertosol were significant at 4 h and 24 h. These interactions were possibly due to the difference in timing at which soil microbes were stimulated and not due to lack of tillage effect in RES+Till treatment, unlike in the first simulated tillage event in Chromosol. For example, at 4 h, RES+Till emitted 45% less CO_2-C compared with the RES-Till. This may be explained by the observation that RES+Till released 2.7 times more than RES-Till at 1 h because the soil disturbance stimulated a large release within first few hours.

Soil microbes responded slowly to the addition of water in RES-Till treatment at 1 h while there was maximum stimulation in RES+Till. At 4 h, 8 h and 24 h, emission was higher for RES-Till, not because of lack of tillage in RES+Till but because of differences in timing of microbial stimulation. RES significantly affected CO_2-C evolution at all sampling times except for 168 h for both soils and -24 h for Vertosol due to the availability of a labile C pool. The +Till effect was only significant at 1 h, with a more pronounced effect in the clayey Vertosol, which had more soil C.

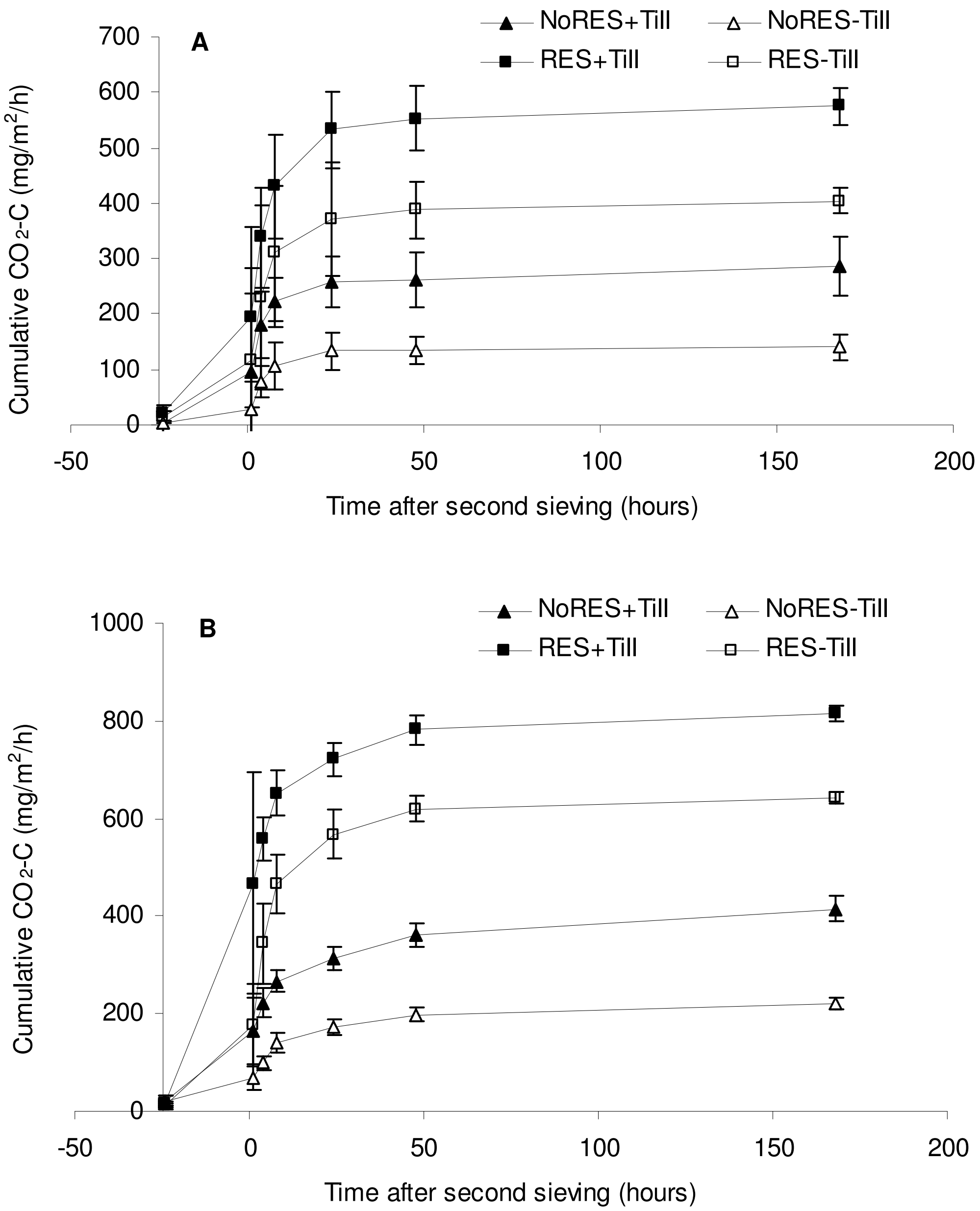


Figure 6.3. Cumulative CO_2-C flux for the second simulated tillage. Means ± standard errors (vertical bars) are presented. A = Chromosol; B = Vertosol; NoRES-Till = without residue and unsieved; NoRES+Till = without residue and sieved; RES-Till = residue incorporated and unsieved; RES+Till = residue incorporated and sieved.

The ANOVA for total CO_2-C evolved showed that the main factors of soil type, residue incorporation and simulated tillage had individually influenced the CO_2-C evolution at $P < 0.001$. But there were no significant interactions between any of the three factors. On average, residue incorporated treatments emitted 2.3 times more CO_2-C in comparison to NoRES and +Till emitted 1.5 times more CO_2-C. The NoRES-Till treatment (conventional scenario) emitted the least amount and the RES+Till treatment (organic scenario) emitted the highest quantity. Comparing the two soils, Vertosol emitted 1.5 times more CO_2-C than Chromosol.

6.3.3 Soil C and other soil parameters

In Chromosol, the TOC did not interact with residue and simulated tillage, but in Vertosol they interacted significantly because RES+Till had 14% more TOC compared with NoRES+Till (Table 6.2). The residue incorporation highly influenced the TOC and TN in both Chromosol and Vertosol, whilst simulated tillage did not influence TOC and TN in either soil type. The C:N ratio was unaffected in the sandy Chromosol, but there was an increase for clayey Vertosol.

Table 6.2. Total organic carbon (TOC), total nitrogen (TN) and C:N ratio in Chromosol and Vertosol. Means and standard errors (se) are shown for each treatment and the statistical significance levels from the ANOVA are given. NoRES-Till = without residue and unsieved; NoRES+Till = without residue and sieved; RES-Till = residue incorporated and unsieved; RES+Till = residue incorporated and sieved.

	NoRES-Till	NoRES+Till	RES-Till	RES+Till	se	Significance level		
						RES	Till	RES × Till
Chromosol								
TOC (g/100g)	1.24	1.22	1.47	1.44	0.064	***	ns	ns [a]
TN (g/100g)	0.119	0.119	0.142	0.138	0.0062	***	ns	**
C:N ratio	10.46	10.30	10.32	10.47	0.044	ns	ns	ns
Vertosol								
TOC (g/100g)	2.06	2.01	2.26	2.29	0.0705	***	ns	*
TN (g/100g)	0.188	0.187	0.203	0.200	0.004	***	ns	ns
C:N ratio	10.92	10.75	11.16	11.45	0.153	***	ns	*

Notes: [a] = square root transformed to stabilised variances, se = standard error, Significance level: $*P < 0.05$, $**P = < 0.01$, $***P = < 0.001$, ns = not significant.

6.3.4 Change in soil C

Total C lost (TOC_{Δ}) was highly significant for soil type and residue incorporation, but simulated tillage were not significant (Figure 6.4). Residue and simulated tillage did not interact significantly. The residue incorporated treatments showed the maximum decrease, but the unamended treatments saw the least decrease.

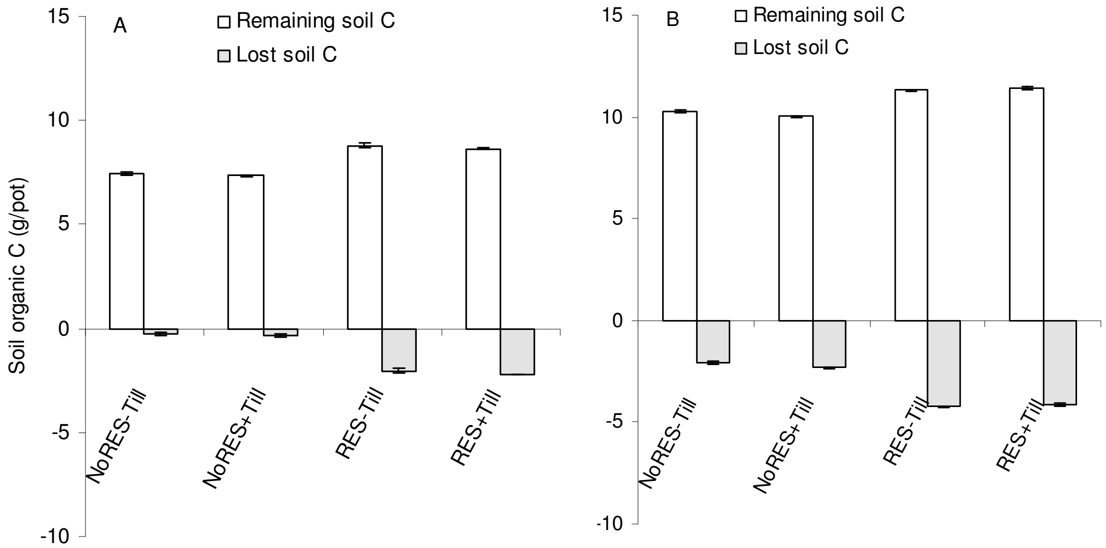


Figure 6.4. Remaining verses lost soil organic carbon in two soil types. Means ± standard errors (vertical bars) are presented. A= Chromosol and B= Vertosol. Estimated average values presented. NoRES-Till = without residue and unsieved; NoRES+Till = without residue and sieved; RES-Till = residue incorporated and unsieved; RES+Till = residue incorporated and sieved.

6.4 Discussion

6.4.1 CO_2-C flux

The trend for cumulative CO_2-C flux for the first simulated tillage event shows that bulk of the activity occurred between 1 h and 120 h after simulated tillage, where we presume most flux occurred. For the second simulated tillage event, CO_2-C flux was measured at more frequent time intervals up to 48 h after the simulated tillage (Figure 6.3). This captured the flux trend the over time with more precision and better representing microbial activity occurring after soil disturbance, thus we focus the discussion on the second event. The patterns of cumulative CO_2-C fluxes demonstrated are in the order NoRES-Till < NoRES+Till < RES-Till < RES+Till for both soil types. This indicates that soil disturbance increases the rate CO_2-C flux in short-term (Ellert and Janzen 1999, Wuest *et al.* 2003) either in absence or presence of incorporated residue. These trends are corroborated by findings for laboratory (Roberts and Chan 1990, Calderón *et al.* 2000, Wuest *et al.* 2003) and field (Ellert and Janzen 1999, Gesch *et al.* 2007) trials in terms of CO_2-C flux peaking within first hour after disturbance and decreasing later, irrespective of residues being applied or not. Similarly, traditional tillage were found to emit higher levels of CO_2 than the no-tillage system in a short-term study under field conditions (Carbonell-Bojollo *et al.* 2011).

The increase in CO_2-C flux after soil disturbance can be attributed to improvement in soil aeration (Wuest *et al.* 2003) and to the availability of labile substrate for microbial action

(Tisdall and Oades 1982, Kuzyakov 2006). Also, water applied after simulated tillage led to an increase in microbial activity. Within residue treatments, RES+Till have evolved significantly higher flux of C than the RES-Till treatment and so RES-Till treatment acts as a sink for CO_2 but the RES+Till treatment as a source. The synergy of residue incorporation and simulated tillage in producing the highest levels of CO_2-C flux for the RES+Till treatment is related to both the availability of labile substrate and the soil disturbance improving soil aeration boosting microbial respiration.

The ANOVA for the total CO_2-C emitted for second event over the sampling time showed that soil type, residue incorporation and simulated tillage had individually influenced the CO_2-C evolution. The soil types differed significantly because of the initial differences soil C concentration (Table 6.1), whereby on average, SOC-rich Vertosol emitted 1.5 times more CO_2-C than the SOC-poor Chromosol. The labile C from residue input in soil promotes fast recovery of soil structure (Tisdall and Oades 1982) and turnover times for macro-aggregates are within 40 to 60 days (De Gryze *et al.* 2005). Our four months of pre-incubation before simulating tillage then should have sufficiently allowed for the formation macro-aggregates. The physical force associated with sieving disrupts the any structure of soil aggregates and increases inter-aggregate pore spaces (Schjønning and Rasmussen 2000, Six *et al.* 2000a) leading to decomposition of the protected C in structural pores as CO_2 (Six *et al.* 2000a, Mikha and Rice 2004, Conant *et al.* 2007).

Due to labile C input from residue (Tisdall and Oades 1982, Kuzyakov 2006), residue incorporated treatments emitted 2.3 times more, on average, in comparison with unamended (NoRES) treatments across the two soil types. Simulated tillage impacted significantly due to increases in C mineralisation caused by improvements in soil aeration (Wuest *et al.* 2003) and soil and residue contact (Angers *et al.* 1993) resulting in release of 1.5 times more CO_2-C, on average. Both of our key variables of residue and simulated tillage were individually contributing significantly more CO_2-C. Our conventional SMS scenario treatment (noRES-Till) emitted less CO_2-C into the atmosphere than the organic SMS scenario (RES+Till). This may lead to biased conclusion about C balance if we do not consider C remaining in the soil. It should be also noted that the data presented are the indications under laboratory conditions and output of a short term study.

6.4.2 Remaining soil C and C:N ratio

In Chromosol, the TOC did not interact with residue and simulated tillage, but in Vertosol they interacted significantly because RES+Till had 14% more TOC compared with NoRES+Till. Residue had a highly significant impact on the concentrations of TOC between treatments because of C from residue. In Chromosol, the residue incorporated treatments, on average, had 18% more TOC than the treatments without residue. However, there were smaller responses in Vertosol with residue incorporated treatment, averaging at 12% more TOC than the treatments without residue because of its initial higher C content. Yet simulated tillage had no significant impact on the level of TOC in both soil types. In agreement with our findings, Calderón *et al* (2000) and Kristensen *et al.* (2003) have reported the limited effect of simulated tillage on mineralisation of soil carbon and nitrogen. Roberts and Chan (1990) found that the total C losses due to simulated tillage in the range of 0.0005% to 0.0037% in Australian Chromosols which is a very small proportion as compared to the C content in the soil.

Under field conditions, no significant differences between tilled and no-till (in five years period) were also reported in a meta-analysis of 69 paired sites experiments in terms of SOC (Luo *et al.* 2010a), consistent with our results. Blanco-Canqui and Lal (2008) reported that there was no consistency between no-till and plough till in terms of SOC in the United States. The C:N ratio was unaffected in the sandy Chromosol, but there was an increase for Vertosol because more carbon particles from residue might have been adsorbed on its organo-mineral complexes that help stabilise carbon (von Lützow *et al.* 2006) mainly due to the high clay content. The high-activity clays like smectites in Vertisols provide better sorption for carbon molecules than the low-activity clays such as kaolinite in the Alfisols (Bronick and Lal 2005). Physical stabilisation through microaggregation is also likely in the Vertosol, thus protecting SOC from decomposition. Six *et al.* (2002a) and Blanco-Canqui and Lal (2004) refer to 'protection' and 'entrapment' respectively for this physical stabilisation mechanism.

The organic farming requires the high levels of organic materials input to maintain soil fertility and so are better than conventional farming for SOC storage (Mäder *et al.* 2002, Mondelaers *et al.* 2009). However, organic farming relies on tillage for weed control which can reduce SOC. The organic scenario treatment of RES+Till not only emitted more CO_2 but also had 16% and 11% higher level of TOC in Chromosol and Vertosol, respectively, compared with the conventional scenario treatment NoRES-Till where weeds are controlled by non-tillage methods (herbicides). Since the CO_2-C emitted is usually a minute fraction, for example, in a range of 0.0005% to 0.0037% of the soil carbon (Roberts and Chan, 1990) the C lost as CO_2-C by soil disturbance is more than compensated for by addition of residue.

6.4.3 Change in soil C

Relative change in soil may be a better indicator of soil C balance in response to management operations than a snapshot of soil C or total CO_2-C emission. The relative change in soil C over the duration of the experiment provides an understanding of the quantity of C lost. In both soil types, the RES+Till (organic scenario) treatments had higher percentages of remaining soil C at the end of experiment than the NoRES-Till (conventional scenario) because of the greater C input from incorporated residue, an important component of organic farming systems (Bell *et al.* 2012). Interpretations based CO_2-C flux figures alone may be misleading and should be interpreted in relation to the total soil C pool before and after a trial. For example, Luo *et al.* (2010b) conducted a review of 20 published papers on the effect of tillage on the change of soil C relative to adjacent native systems and reported that there was exponential loss soil C due to cropping. They have shown that most of the loss had occurred within 10 years of tillage from 0.1m depth.

In conclusion, the residue incorporation had a larger effect on CO_2-C flux than simulated tillage for both soil types, suggesting that C availability and form can be more important than disturbance in cropping soils. Soil disturbance increases the rate CO_2-C flux in short-term either in absence or presence of residue. The treatment of RES+Till appears as the source CO_2 but the RES-Till as the sink of CO_2, when only emissions are considered. The apparent differences are insignificant it terms of soil C content. The RES+Till (organic scenario) treatments had 16% and 11% more soil C in Chromosol and Vertosol, respectively, in terms of remaining soil C content in comparison to NoRES-Till (conventional scenario) confirming the observation that organic systems can sequester more soil C. The C lost by soil disturbance was more than compensated by incorporation of residue. This experiment was conducted under laboratory conditions and may not reflect field conditions. Since it is a short term study the data presented are the indications under laboratory conditions and so should be treated as such. The change in soil C content over time may be better indicator of soil C balance between CO_2-C loss and soil remaining in the soil. However, in interpreting data from this paper the short timeframe of the study should be acknowledged.

Chapter 7. General conclusion

7.1 Introduction

Maintaining soil organic carbon (SOC) stocks in vegetable production systems, especially organic ones, is a major challenge because frequent and intensive cultivations used for management operations such as bed preparation and weed management (Bond and Grundy 2001, Bàrberi 2006, Chirinda *et al.* 2010), have a negative impact soil C levels (Angers *et al.* 1993, Six *et al.* 1999, von Lützow *et al.* 2006). Despite requiring multiple cultivation operations, the vegetable systems are characterised by little or no crop residue input (Jackson *et al.* 2004, Chan *et al.* 2007). In this light, sweet corn, a high residue vegetable crop, was proposed as a rotation crop for a vegetable system.

Chapter 3 examined the effect of organic and conventional soil management systems (SMS) with or without residue incorporation on yields of and nutrient uptake by sweet corn and cabbage and on soil nutrients. The role of decomposing residue in suppression of weeds was another topic presented in Chapter 3. Chapter 4 was focused on the effect of residue incorporation and SMS on the total organic C (TOC) concentration, SOC stock and microbial biomass C (MBC) in the field experiment. A laboratory experiment separating the confounding factors of SMS (i.e. herbicide and mineral fertiliser in the conventional SMS, and cultivation and organic fertiliser in the organic SMS) was also presented in Chapter 4. Chapter 5 followed on to further investigate the effect of treatments on TOC fractions of particulate organic C (POC), dissolve organic C (DOC) and mineral-associated C (MOC) from the field and laboratory experiments. Chapter 6 dealt with the effect of residue incorporation and simulated tillage (soil disturbance by sieving), two potentially opposing factors of TOC, on the emission of CO_2-C under laboratory conditions.

The subsequent sections of this chapter dwell on the key findings in relation to the research objectives, the main implications, and limitations and future directions for research.

7.2 Key findings and synthesis

Yields of both crops under the organic SMS were not lower than the conventional SMS as opposed to what is generally reported (Pimentel *et al.* 2005, Azadi *et al.* 2011), possibly due to the equivalent N, P and K nutrients applied. Further, soil nutrient status might not have reached the limiting level after imposition of the treatment. Nutrient uptake by corn stover (except P) and cabbage head were not influenced by residue incorporation or SMS (Chapter 3). The higher P content in organic SMS was found in corn stover only and not in cabbage head. The literature on food nutrition also reports a lack of clear, consistent differences between the nutrient contents of organic and conventional produce (Biao *et al.* 2003, Hoefkens *et al.* 2009, Smith-Spangler *et al.* 2012).

Corn residue incorporation reduced weed biomass in cabbage crops in both years. Such residue-induced inhibitions of weed biomass have the potential to be a supplementary tool to mechanical weed control for the organic SMS (Fisk *et al.* 2001, Mennan *et al.* 2009), which might possibly reduce the negative effects of tillage on SOC for organic growers and may reduce on the cost of herbicide for conventional farmers.

Residue incorporation and the organic SMS increased the average total N, indicating the longer-term fertility gains of those treatments. Exchangeable K, but not Colwell P, in the soil was significantly influenced by residue incorporation, however, K and P were not lower in the organic SMS, consistent with other research on organic vegetable systems in Australia (Nachimuthu *et al.* 2012). Although soil structural stability was not significantly influenced by residue and SMS, the residue incorporated treatments generally had slightly higher average electrochemical stability index (ESI) values suggesting the positive influence of residue on the soil aggregate stability (Six *et al.* 2002a, Blanco-Canqui and Lal 2004).

The amount of atmospheric CO_2-C assimilated in the corn residue, a key focus of the research, was not affected by SMS or residue incorporation, but was affected by soil type and year (Chapter 3). However, soil total organic C (TOC) concentration of the field experiment was consistently increased by the incorporation of shredded residue (Chapter 4). The effect of SMS on TOC was inconsistent and depended upon the time interval between organic fertiliser application and soil sampling; when this interval was longer, the effect disappeared due to mineralisation facilitated by the low C:N ratios of organic fertilisers. Evaluation of the SOC stock determined that residue incorporation at about 15 Mg/ha per year (oven-dry equivalent) in soil accumulated an average of 0.96 and 1.22 Mg C/ha for Chromosol and Vertosol, respectively, in the field trial after 2 years. Declining SOC levels due to little or no crop residue input and multiple cultivations in vegetable systems (Jackson *et al.* 2004, Chan *et al.*

2007) could be improved using sweet corn in rotations and incorporating its residue in the soil. Clark *et al.* (1998) had also reported such positive results.

When the confounding factors of the SMS treatments in the field experiment were separated in an incubation experiment, the use of atrazine and mineral fertiliser in the conventional SMS was found to have no significant effect on TOC concentration, whereas the organic fertiliser increased TOC whilst simulated tillage decreased it in an organic SMS scenario (Chapter 4). The latter results confirmed that organic fertiliser application is capable of balancing the C lost through tillage in the organic vegetable systems. The consequence of the slight decrease of TOC in the mineral fertiliser treatment combined with the slight TOC increase in the organic fertiliser treatment meant that the two fertiliser treatments were significantly different to each other. This corroborates the observation that the former might accelerate mineralisation of TOC (Khan *et al.* 2007, Russell *et al.* 2009) whilst the latter increases TOC through physical addition of C and changes to soil function (Wells *et al.* 2000, Pimentel *et al.* 2005).

Investigating further, from TOC to its fractions, residue incorporation in soil was found to increase the labile fractions of particulate organic C (POC) and dissolved organic C (DOC) and the stable fraction of mineral-associated organic C (MOC) in both field and laboratory experiments alike (Chapter 5). These results demonstrated that residue incorporation could not only increase labile fractions, but also stable ones. As MOC was found to be the major pool of TOC in both experiments, the short-term gains observed have the potential to translate into longer-term C sequestration. This is because MOC is the stable fraction formed by binding of C molecules on silt plus clay minerals, a mechanism that is considered as a means of long-term C sequestration in soil (Hassink 1997, Kögel-Knabner *et al.* 2008). Therefore, the role of physicochemical stabilisation mechanism (Hassink 1997, Christensen 2001, von Lützow *et al.* 2006) was more prominent, than through the aggregation model (Six *et al.* 2002a, Blanco-Canqui and Lal 2004) as the tillage operations of vegetable systems would disrupt soil structure and aggregates (Bàrberi 2006).

However, SMS only influenced DOC significantly, not POC and MOC, possibly due to mineralisation of organic fertilisers facilitated by low C:N ratios to release in the dissolved form of soil C and CO_2-C emission.

Soil microbial biomass C (MBC) data showed that soil's biological fertility was improved by residue and by combining residue with organic fertiliser. The MBC was generally in the order: Org+RES > Conv+RES > Org-RES > Conv-RES[1], indicating an increase in labile C in the soil (Carter *et al.* 1999, Wang *et al.* 2003) as MBC is a surrogate measure of labile soil C. Therefore, incorporation of either residue or organic fertiliser or both increased the biologically active pool of C, the breakdown of which would release nutrients for plant growth, whether in organic or conventional SMS (O'Donnell *et al.* 2001).

When the effect of residue incorporation and simulated tillage, two potentially opposing factors affecting of TOC, were tested for the emission of CO_2-C, both factors significantly increased emissions. However, the effect of residue was more pronounced than that of simulated tillage, suggesting that the availability and form of labile substrate could be more important than physical disturbance in cropping soils. The organic scenario (residue incorporated and soil sieved treatment) not only emitted more CO_2-C but also had higher levels of TOC compared with the conventional scenario (no residue incorporated, nor soil sieved), confirming the observation that an organic system might retain more soil C than a conventional system (Wells *et al.* 2000).

Since the CO_2-C emitted is usually a minute fraction in relation to TOC (Roberts and Chan 1990), the C lost by soil disturbance is more than compensated by the incorporation of residue. Soil disturbance by simulated tillage decreased TOC in the experiment where confounding factors were separated possibly due to low C:N ratios of the organic fertiliser (Chapter 4), whereas simulated tillage had a limited impact on POC, MOC and TOC (Chapter 5) possibly due to the high C:N ratio of the corn residue. This suggests that the effect of soil disturbance by sieving on TOC was related to the C:N ratios of the incorporated materials and that negative effect of cultivation on TOC could be balanced by organic fertiliser (Chapter 4) and could more be than offset by residue (Chapter 6), respectively.

Comparing soil types, the clayey Vertosol conserved higher levels of soil nutrients, had better soil structural stability, higher levels of TOC, MOC and MBC concentration and stored more SOC stocks than the sandy Chromosol. However, the SOC-rich Vertosol also emitted more

[1] Conv±RES = conventional soil management treatments with or without residue incorporation and Org±RES = Organic soil management treatments with or without residue incorporation.

CO_2-C than the SOC-poor Chromosol. There differences were expected based on the known properties of each soil type (McKenzie *et al.* 2002).

The cycle of investigation was therefore completed from the sequestering of atmospheric CO_2-C in the form of corn residue followed by its incorporation in soil to form TOC and its fractions, to finally examining the effect of simulated tillage and residue incorporation on emission of CO_2-C.

7.3 Theoretical and practical implications

Sweet corn not only produces about 1.7 times more biomass carbon than most other grain crops (Wilhelm *et al.* 2004) but is also a relatively high value vegetable crop that is suitable as a rotation crop in a vegetable enterprise. Regarding the suitability of soil types, major vegetable growing areas in Australia are concentrated on Vertosols (e.g. south-east Queensland) and less under Chromosol. Sweet corn is an important vegetable crop in Australia with annual sweet corn production is estimated at 62,575 Mg from the total area of 5,942 ha (Rab *et al.* 2008). It is, therefore, possible to integrate sweet corn in annual cropping cycles of a vegetable enterprise. While shredding residue was undertaken in our trials, it is unlikely to be a practical option for growers because shredding may incur additional production cost and no short-term productivity gains were found to accrue according to yields of both corn and cabbage. However, the results highlight the potential for increasing soil C using crop residues (Alvarez 2005, Alijani *et al.* 2012) to benefit soil structure (Six *et al.* 2002a, Blanco-Canqui and Lal 2004), soil water holding capacity (Lotter *et al.* 2003, Wilhelm *et al.* 2004) and soil nutrients (Wells *et al.* 2000, Berry *et al.* 2002).

Sequestering atmospheric CO_2 in the form of sweet corn residues and then incorporating these residues in the soil can have potentials in net transferring of atmospheric CO_2-C into the soils (Powlson *et al.* 2011). The findings demonstrated that under irrigated field conditions in Australia, it is biophysically feasible to accumulate or increase TOC concentration, SOC stock, soil MBC or the both the labile (particulate organic C) and stable (mineral-associated organic C) carbon fractions, with the incorporation of shredded sweet corn residue in a vegetable system. Increased soil TOC via the incorporation of chopped corn residue is also reported for Iraqi conditions (Alijani *et al.* 2012).

Although, the effects of SMS on TOC was variable and organic fertiliser increased TOC if measured within six months of incorporation, these effects depended on the time interval between fertiliser incorporation and soil sampling. In the literature, soil C in organic systems is generally reported to be higher than in conventional systems (Clark *et al.* 1998, Teasdale *et al.* 2007, Mancinelli *et al.* 2010) but inconsistencies do exist (Fließbach *et al.* 2007, Leifeld *et al.* 2009).

A number of theoretical implications may be identified from the outcomes of this research. Firstly, the declining SOC situation in vegetable systems (Jackson *et al.* 2004, Chan *et al.* 2007) could be improved in the medium- to long-term, with benefits for crop productivity and profitability (Lal 2004, Pacala and Socolow 2004) of the vegetable enterprises. Secondly, the consequential net reduction of atmospheric CO_2-C concentrations could help mitigate climate change slightly. Since the soil C pool is three times the atmospheric C pool, even a small increase in magnitude of soil C across the large land areas can potentially reduce atmospheric CO_2-C concentrations (Trumbore *et al.* 1996, Davidson and Janssens 2006). The magnitude of the theoretical reduction would be proportional to the size of land area devoted to the practice of incorporating sweet corn residues.

Data from the fractionation work in the field and laboratory experiments consistently showed that the increase in TOC was due to increase in both labile and stable fractions. Since a major proportion of TOC ($\geq$ 83% in the Vertosol and $\geq$ 73% in the Chromosol) was found to be MOC, physicochemical stabilisation might be considered as a key mechanism for long term sequestration of C in soil (Hassink 1997, Kögel-Knabner *et al.* 2008) in a vegetable production system.

Soil incorporation of residue and organic SMS are separately capable of improving soil nutrient availability, especially N and K, indicating the potential long-term fertility gains of these treatments. The slower nutrient releasing characteristics of organic fertiliser and crop residue can not only benefit successive crops but also reduce nutrient losses to the environment (Berry *et al.* 2002, Marinari *et al.* 2010a), though nutrient losses through leaching and erosion remain a concern (Chan *et al.* 2007).

With regard to weed management, the significant reduction of weed biomass in cabbage, brought about by the suppression of germination and growth by decomposing residue (Weston 1996, Mennan *et al.* 2009), could be exploited as a supplementary weed control strategy for both organic and conventional farmers. There is the possibility of reducing the intensity or frequency of tillage operations, thereby reducing soil disturbance (less mineralisation SOC), especially in organic farms. Further, organic farmers could save on tillage cost and the conventional ones on the cost of herbicide.

7.4 Policy implications

The outcomes of this research are relevant to the policy strategies of the Australian Government which articulate a reduction of green house gas emissions (Commonwealth of Australia 2011). There is potential for increasing SOC levels within the vegetable farms if vegetable growers add sufficient quantities of organic materials (organic fertilisers, manure, crop residues, etc) to soils (McKenzie *et al.* 2002, Sanderman *et al.* 2010). Farmers may generate credits for reducing emissions and/or sequestering C in soil through the Clean Development Mechanism of the Kyoto Protocol (Zomer *et al.* 2008) and the Carbon Farming Initiative (Commonwealth of Australia 2011) of the Australian Government. Although the agriculture sector is not currently included in the C pricing policy, the Carbon Farming Initiative is designed to 'create economic rewards' so that farmers and land managers have a monetary incentive to reduce pollution or store C in the land (Zomer *et al.* 2008, Commonwealth of Australia 2011). Incorporation of crop residues and utilisation of organic materials as a means of maintaining soil fertility, especially in alternative farming systems such as organic ones, are expected to contribute positively toward long-term C sequestration in soils under the Carbon Farming Initiative.

7.5 Limitations and future research directions

In the initial stages of the experimentation, only changes in TOC concentration was considered and not the changes in SOC stock. So bulk density was not measured except for the December 2011 samples. This is why SOC stock was determined only at the end of experimentation. Measurement of bulk density is recommended to be carried out at every sampling time in such studies to enable estimation of SOC stock changes over time. However, the relative SOC stock change between treatments over the 2-year experiment provides a useful indication of benefits of residue incorporation on SOC stock.

Another oversight was regarding not determining of soil water content (SWC) of the soil through out the experimentation. Such data would have allowed the research to determine if the incorporation of residue and organic fertiliser could help conserve water in the soil. SWC was determined in December 2011, but the data did not show any treatment effects (except soil types) due to prolonged rainfall prior to sampling, and was not presented in the thesis. Monthly monitoring SWC using simple non-destructive methods like the use Time Domain Reflectometry could have been performed and such measurements are recommended in future work.

Farming systems research trials need a longer time frame (Pimentel *et al.* 2005, Leifeld *et al.* 2009) to produce conclusive evidence of system performance. In that light, a long term trial studying the effect of sweet corn residue incorporation in soil especially under vegetable systems is recommended. Even if such trials are not related directly to farmers practice, long-term studies would improve the understanding of soil C dynamics in frequently cultivated vegetable soils.

More research on the residue-induced inhibitions on weed biomass is recommended to evaluate the suitability of developing residue incorporation as a supplementary tool to mechanical and herbicidal weed control for organic and conventional SMS, respectively. Aspects such as residue source, incorporation methods, soil type and weed species selectivity warrant further research.

Due to resource and time constraints, the CO_2-C emission experiment was conducted under laboratory conditions, which did not reflect other issues like soil compaction, erosion and run off that are facilitated by tillage in field conditions. Recognising this limitation, it is recommended that the measurement CO_2-C emissions should be integrated within the future field experiments using automated measurement systems (sensors). However, it is difficult to control various factors like moisture and temperature in the field, unlike under laboratory conditions.

Corn cobs and roots samples for 2010 were lost in a fire accident before performing chemical analyses and so only yields of cobs (not nutrient uptake) are reported for both years.

Incessant rainfall spread throughout the cabbage cropping season in 2010 and heavy rainfall in 2011 impeded timely sampling of soil. The unusual rainfall (amount and pattern) could have distorted the results due to leaching of soil solutes or by creating waterlogged soil conditions for extended periods. The above mentioned rainfalls also affected the schedule of research activities.

7.6 Conclusion

Residue incorporation in soil can increase soil C in a corn-cabbage rotation, but the effect of SMS was inconsistent. Though shredding of residue may not be practical for growers, the results highlight the potential for increasing soil C using crop residues in vegetable production systems. The increase in the stable form of C, not just in the labile forms, indicates the potential for longer term C sequestration in soil through physicochemical stabilisation. A simulated tillage experiment showed that the organic SMS scenario with residue can accumulate more soil C, even if it emits more CO_2-C (a very minute fraction of soil C), than the conventional SMS scenario (without residue).

Soil incorporation of residue and organic SMS are separately capable improving soil nutrient availability indicating potential long-term fertility gains. The slower nutrient releasing characteristics of organic fertiliser and crop residue can not only benefit successive crops, but also may reduce nutrient losses to the environment. The residue-induced inhibitions of weed biomass may be used to supplement mechanical and herbicidal weed control for the organic and conventional SMS, respectively.

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